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Demonstration/Evaluation of the Cat-Ox Flue Gas Desulfurization System

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DEMONSTRATION/EVALUATION OF THE CAT-OX FLUE GAS DESULFURIZATION SYSTEM—FINAL REPORT

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16. ABSTRACT The report gives a comprehensive summary of the experience gained and the problems encountered during the Cat-Ox demonstration program. The report outlines the process design and construction, as well as operating experience and problems. Test results and conclusions derived from baseline testing, acceptance testing, ESP testing, transient testing, and a number of special tests and studies associated with the system are reported.

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by

R. Bee, R. Reale, and A. Wallo

The Mitre Corporation/Metrek Division
Westgate Research Park
McLean, Virginia 22101

Contract No. 68-02-0650
ROAP 21ACZ
Program Element No. 1AB013

EPA Project Officer: Charles J. Chatlynne

Industrial Environmental Research Laboratory
Office of Energy, Minerals and Industry
Research Triangle Park, N.C. 27711

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- Dow Chemical Corporation,
- Midwest Research Institute,
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- Southern Research Institute.

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SECTION I

EXECUTIVE SUMMARY

INTRODUCTION

The catalytic oxidation (Cat-Ox)[*] process is a regenerable type of flue gas desulfurization process. The process controls sulfur dioxide (SO_2) emissions through the catalytic oxidation of SO_2 to sulfur trioxide (SO_3). The SO_3 is then collected as sulfuric acid in an absorbing tower. Cat-Ox is Monsanto Enviro-Chem's (MEC) adaptation of the contact sulfuric acid process for SO_2 control.

The EPA/Illinois Power co-funded Cat-Ox demonstration system constructed at the Illinois Power Company Wood River facility was a retrofit application in which the system was attached to the 100 MW Unit No. 4 boiler. A conceptual diagram of the system is shown in Figure 1 and a picture in Figure 2. The prime objectives of the system were to (1) remove 85 percent of the SO_2, and (2) remove essentially 100 percent of the particulate matter from the flue gas.

SYSTEM DESCRIPTION

Figure 1 and Figure 2 show the major subsystems of the demonstration process. They include:

1. Fly Ash Collection
2. Flue Gas Reheat and Heat Recovery System
3. Conversion System

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[*] Cat-Ox is the registered trademark of Monsanto Enviro-Chem Systems, Inc.

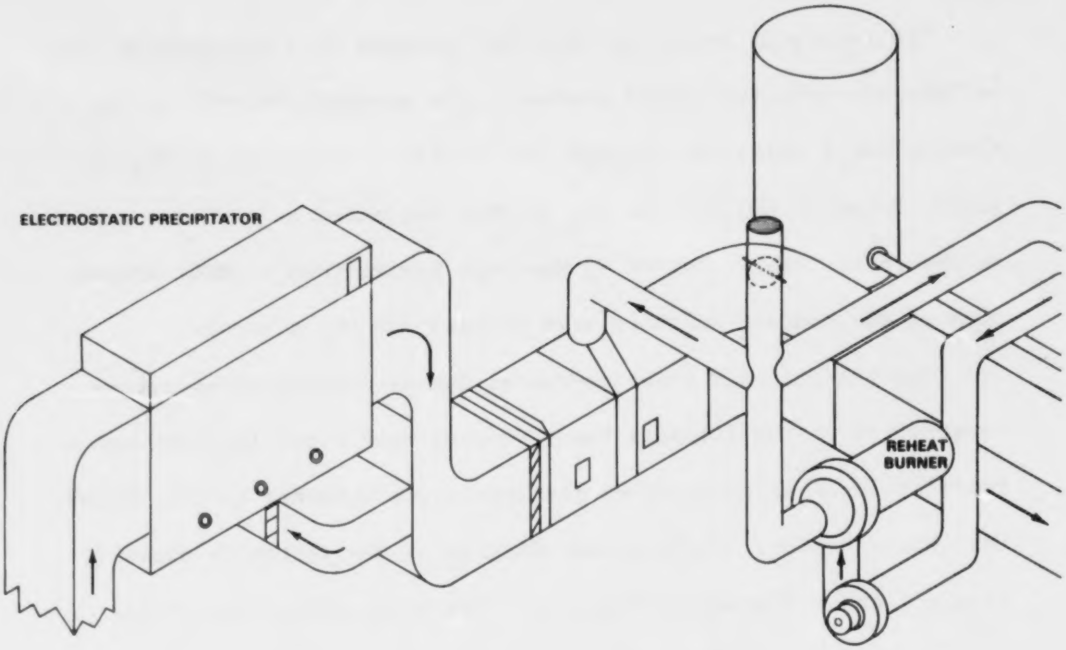
ELECTROSTATIC PRECIPITATOR
REHEAT BURNER

FIGURE 1
CONCEPTUAL DIAGRAM OF THE CAT-OX DEMONSTRATION UNIT

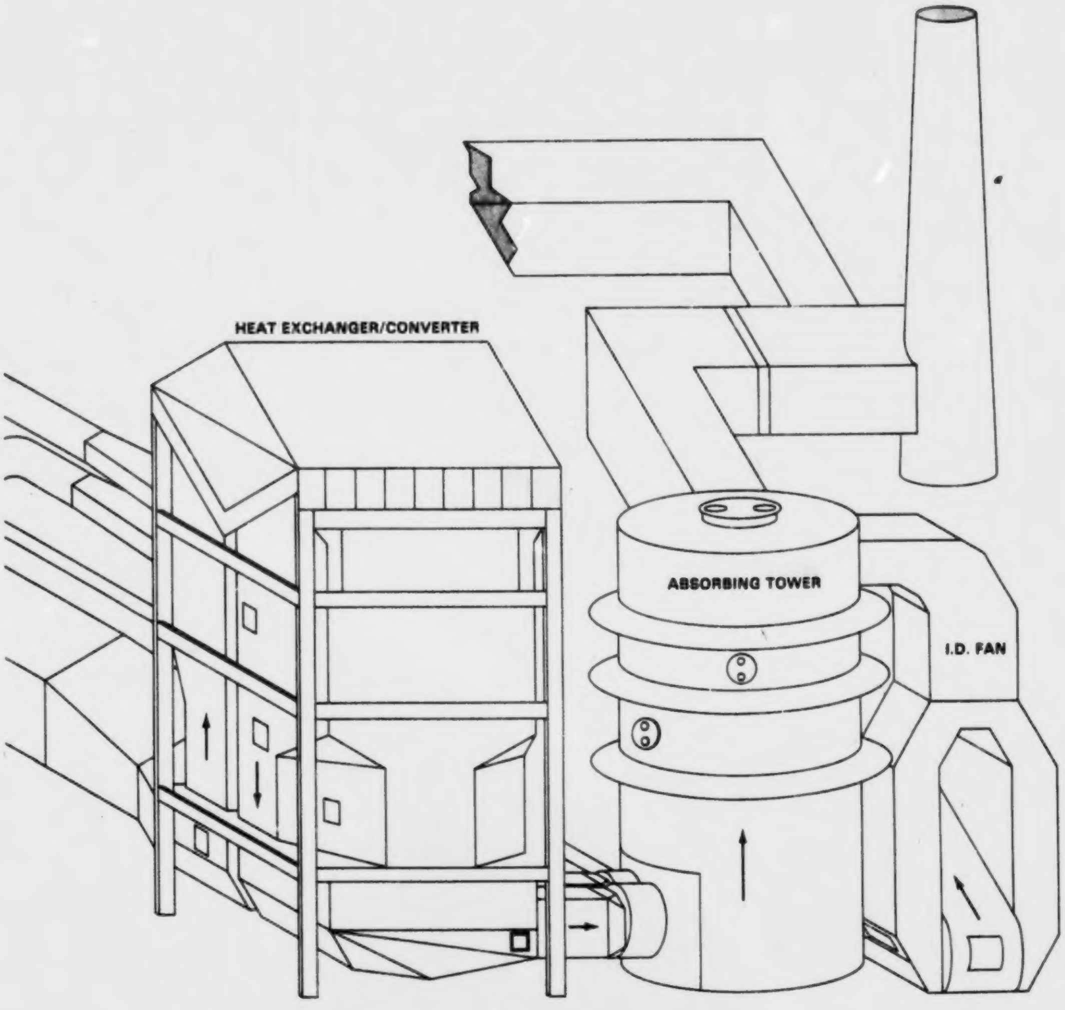
HEAT EXCHANGER/CONVERTER
ABSORBING TOWER
I.D. FAN

FIGURE 1
CONCEPTUAL DIAGRAM OF THE CAT-OX
DEMONSTRATION UNIT
(CONTINUED)

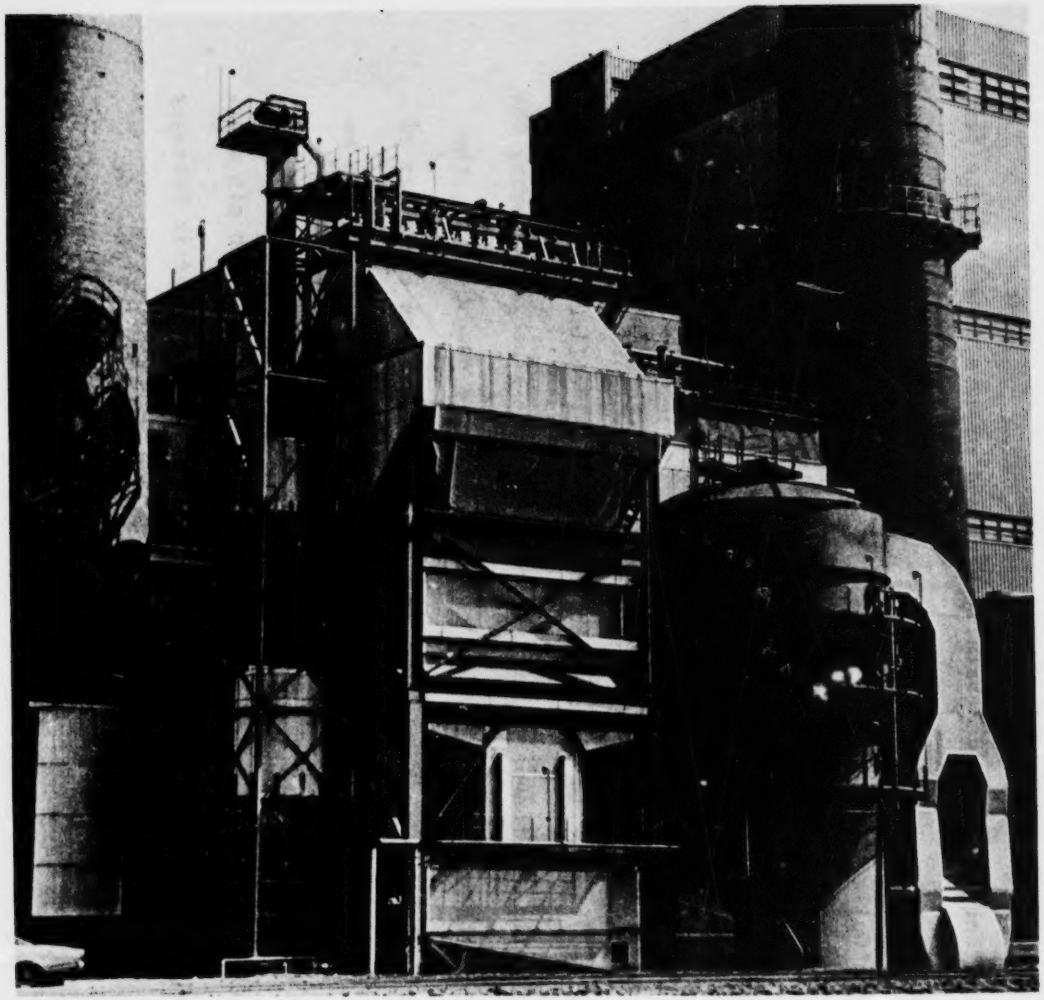

FIGURE 2

EPA/IPC DEMONSTRATION CAT-OX PROCESS

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4. Absorbing Tower
5. Acid Mist Eliminator
6. Product Handling Storage and Loading
7. Cat-Ox ID Fan.

The systems are described briefly here and in more detail in the text of the report.

Fly Ash Collection

The existing mechanical particle collector was retained in service on Unit No. 4 to remove most of the fly ash from the flue gas. A new Research-Cottrell electrostatic precipitator designed to reduce grain loading in the flue gas from 1.5 to 0.005 grains/SCF was installed to work in series with the mechanical collector to remove essentially all the particulate matter from the flue gas entering the Cat-Ox process. After leaving the electrostatic precipitator, the cleaned flue gas is heated and is then passed into the converter of the Cat-Ox System, or, during start-up or unusual operation, can be by-passed directly to the stack. The fly ash collected by the precipitators is conveyed pneumatically to the existing ash pit area. The electrostatic precipitator installation was completed in February 1972 and has been operating with Unit No. 4 since that time.

Flue Gas Reheat and Heat Recovery System

This system entails an external reheat burner manufactured by Coen (internal reheat burners initially installed were found unsatisfactory) and a Ljungstrom heat exchanger. The system is designed to bring the flue gas temperature from about 310°F at the precipitator outlet to 850°F prior to entering the converter. The Ljungstrom heat exchanger recovers about 400°F of sensible heat from the flue gas leaving the converter and deposits the heat on the input side of the converter. The results are that the overall requirement for added heat is reduced to about 150°F of sensible heat.

Conversion System

Following reheat to conversion temperature, the flue gas enters the converter where SO_2 gas reacts with O_2 in the presence of the Cat-Ox catalyst (a vanadium pentoxide catalyst) to form SO_3.

The system is designed to convert at least 90 percent of the SO_2 to SO_3 by the exothermic reaction with oxygen in the flue gas.

Normal seal leakage in the Ljungstrom regenerative gas heat exchanger, however, allows flue gas to by-pass the converter and reduce the overall removal efficiency of SO_2 to 85 percent.

Absorbing Tower

The converter exit gas containing SO_3 is partially cooled in the Ljungstrom regenerative heat exchanger to a temperature above the acid dew point of the gas and flows to the absorbing tower. The SO_3 in the flue gas does not combine directly with water in appreciable amounts but must be absorbed in the circulating sulfuric acid in the tower packing section and then combined indirectly with water in the acid. Heat of absorption of SO_3 in the acid and the sensible heat removed from the gas raise the circulating acid temperature.

The gas flows counter-current to the acid in the tower and is further cooled to about 250°F. Hot acid flows from the bottom of the tower to the circulating pump and is then pumped through a graphite tubular acid cooler and returned to the tower at the proper temperature. Product acid is pumped to storage after further cooling to maintain a constant acid level in the bottom.

Acid Mist Eliminator

This acid mist eliminator system consists of Monsanto fiber packed elements which continuously remove the sulfuric acid mist from the gas at a high efficiency following SO_3 absorption. The elements are contained in the top of the absorbing tower above the packed section which allows the collected acid to drain into the packed tower. The acid mist eliminator system was designed with a high efficiency such that the SO_3 and acid mist content of the flue gas leaving this mist eliminator was less than the amount normally emitted in the combustion gas from the steam generation boiler.

Product Handling, Storage and Loading

The product acid is cooled and piped to storage tanks where it is held until shipment. The cooled acid at full load amounts to 12 gallons per minute of 78 percent H_2SO_4. This acid is collected in two 400,000 gallon steel storage tanks. An acid loading pump and tank car loading facilities are provided adjacent to the storage tanks. Tank trucks also may be loaded from this station if desired.

Cat-Ox ID Fan

This induced draft fan provides the motive force to overcome the pressure drops over the entire Cat-Ox system.

HISTORY

In 1962, Monsanto Co., Pennsylvania Electric Co., Air Preheater Co., and Research Cottrell Corp. started the pilot plant development of the Cat-Ox process for SO_2 control. The pilot plant operated on a 400 SCFM slip stream from a pulverized coal-fired boiler and proved the feasibility of the basic process operation.

A 15 MW prototype plant (24,000 SCFM) was then developed and tested at Unit No. 2 of Metropolitan Edison Company's Portland station. The system was an integrated system with a "Hot Side" ESP and no reheat system. The plant operated from August of 1967 to June 1970 and accumulated about 8000 hours of operating time.

During the latter part of 1969 and the first part of 1970, Illinois Power Company (IP) was searching for a method to control SO_2 emissions from their coal burning utility boilers. They commissioned Battelle Memorial Institute of Columbus, Ohio, to perform a study of the control methods then available to aid their selection. The study included the use of low sulfur coal as well as available SO_2 removal processes such as limestone scrubbing, the Wellman-Lord Process, Mag-Ox, and Cat-Ox. As a result of this study and their independent considerations, IP selected the Cat-Ox process as a prime candidate for SO_2 control on their Wood River No. 4 coal fired generation unit. Upon making this selection, preliminary talks were initiated by IP with the process supplier, Monsanto Enviro-Chem (MEC). In January of 1970, IP and MEC jointly approached the National Air Pollution Control Administration (NAPCA, the predecessor to the Environmental Protection Agency) inquiring about joint funding of a demonstration project of the Cat-Ox system. After considerable negotiation, a contract was signed on 26 June 1970, between the U.S. Environmental Protection Agency and IP, with MEC as a subcontractor to IP. The contract covered the construction and operation of the Cat-Ox process with capital funding shared approximately equally between EPA and IP. In addition, Illinois Power Company assumed the financial obligations of providing the necessary utilities and of maintaining and operating the Cat-Ox system for a period specified in the contract.

Unit No. 4 at Wood River normally burned approximately 275,000 tons of coal per year with an average sulfur content of 3.1 percent. Based on these figures, the Cat-Ox system could produce about 25,000 tons per year of 78 percent concentration sulfuric acid.

Construction of the Cat-Ox system started in January 1971 and the associated Research-Cottrell precipitator designed for Cat-Ox was completed and placed in service in January 1972. Initial start-up of the sulfur removal equipment occurred on 4 September 1972 using natural gas for the in-line reheat burners. Because of the unavailability of natural gas, it was necessary to try to operate the in-line reheat burners on #2 fuel oil. After a period of testing, it became apparent that an external combustion chamber for flue gas reheat would be required to maintain satisfactory reliability and continuous operation when using oil as the reheat fuel.

Before installation of the external heater, a performance guarantee test was run and satisfactorily completed using #2 oil as fuel in the in-line heaters in July 1973. At this point the total Cat-Ox operating time was approximately 602 hours. During the month of August 1973, the Cat-Ox system was deactivated and laid up in such a manner as to allow for a long outage. The external burner was completed in April of 1974, and attempts were made to place the unit back in operation 7 May 1974.

During the period between May 1974 and April 1975, there were continued attempts to operate the system using the external reheat burners. A number of malfunctions and process component failures occurred which prevented successful completion efforts. The problems included failures of the acid circulation pumps, persistent leaks in acid coolers and circulation system piping as well as burner and burner control problems. After continued efforts to repair and operate Cat-Ox, IP stopped further work on the system, taking the position that some basic system changes (especially in the acid cooler area) were required before Cat-Ox could be successfully operated. This position was stated in a meeting among IP, EPA, and MEC held at Wood River on 17 April 1975. Following the meeting a layup procedure provided by Monsanto was put into effect and Cat-Ox was completely deactivated in a manner that was designed to protect the equipment from freeze or corrosion problems. This was completed in October of 1975.

The Environmental Protection Agency then performed and funded a number of technical and economic studies relating to the costs and benefits of continuing the demonstration program at Wood River. The results of these studies led to a decision to discontinue the project.

CAT-OX PROCESS AND DEMONSTRATION STATUS

The Cat-Ox pilot plant and prototype plant, the 24-hour acceptance test of the Wood River system, and various other tests and studies indicated that the Cat-Ox process is a technically viable process. Current technology for particle control is capable of meeting the inlet requirements for the Cat-Ox process in either the integrated or retrofit systems. The catalytic converter is capable of greater than 90 percent SO_2 to SO_3 conversion efficiency. The 77.7 percent H_2SO_4 concentration can be maintained during steady state and transient operation. However, one study* indicated that lengthy start-up conditions could result in the generation of dilute hot H_2SO_4 which can cause serious corrosion problems within the system.

An economic comparison of Cat-Ox with Mag-Ox and Wellman-Lord/ Allied FGD processes showed that the Cat-Ox process required the highest capital investment and the integrated Cat-Ox had the lowest annual operating costs. The same study indicated that the Cat-Ox process was less sensitive to coal sulfur content than the other processes; however, the Mag-Ox process produced the least impact on the cost of electricity. Although the selling price of the acid and its "saleability" would have a significant effect on the Cat-Ox annualized costs this factor is site-specific and could not be factored into the comparison. The primary market for the dilute impure acid from the Cat-Ox process is the fertilizer industry. This industry consumes over half the sulfuric acid manufactured in the U.S. While the trace elements in the acid produced by Cat-Ox have not been shown to produce detrimental health and environmental effects when used in the agriculture industry, more research is required before any final judgment can be made.

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*Cat-Ox Product Acid Strength Study, The MITRE Corp. M75-88, December 1975.

Though the process design appears technically viable, the Wood River demonstration was plagued with numerous operational problems. The problems were related to two basic areas:

- Design. Certain characteristics or requirements of the system and power plant environment were not accounted for or identified in the initial design of the unit.
  - internal reheat system would not function properly when the system was committed to use oil instead of gas
  - vibration in the power plant environment caused breakage or wear of the graphite heat exchanger (primarily at metal-graphite contact points in the tube bundle)

  - dilute acid caused by lengthy start-ups resulted in serious corrosion in portions of the system

  - cooling water quality was quite variable. Unfiltered raw Mississippi River water varied in quality with the stage of the river. Flood conditions and high river stages caused much silt and debris to be drawn into the cooling water once through system which fouled and plugged tubular type coolers. Pluggage of the induced draft fan lube oil cooler contributed to overheating and damage to the fan bearings and shaft. Small oil cooler tubes did not permit passage of debris in the cooling water. Debris plugged and fouled the graphite acid coolers and probably caused higher flow velocities which may have contributed to graphite tube vibration and breakage as mentioned above due to power plant environmental vibration. The debris also plugged cooling water control valves complicating control of the acid temperatures which caused accelerated corrosion and resulted in many acid spills.

- Operation. Power plant personnel were unfamiliar with chemical plant operations and requirements.

  - personnel were unfamiliar with the operating and maintenance requirements of special alloys, material, and equipment such as duriron recirculating pumps.

  - unfamiliarity with acid handling problems resulted in the corrosion of areas in the product handling system.

These problems combined to result in lengthy delays which further compounded the problems. In addition, long periods of shutdown had an adverse effect on the process and caused serious deterioration of some system components. The only system component that was both operational and functioning without problems since its construction was the electrostatic precipitator.

After continued attempts to operate Cat-Ox, IP halted repair efforts on the system and took the position that some basic modifications to the system design were required for the Cat-Ox demonstration to be successfully completed.

A survey of the plant status funded by EPA indicated that the major problems outlined earlier along with system deterioration problems could be solved but would require a major restoration program.

In the interim, however, IP has chosen to comply with SO_2 standards by burning low sulfur coal in the Unit No. 5 boiler, and physical plant arrangement constraints prevent them from employing a different type of coal for Unit 4. Thus, the demonstration program would have to be run on low sulfur coal. Though the results based on low sulfur fuel operation would be useful, they would leave many serious questions unanswered about Cat-Ox operability. Hence, continuation of the demonstration would be of very limited use; and accordingly, the program was discontinued.

Discontinuation of the demonstration program neither proves nor disproves the feasibility of the Cat-Ox system. However, some inferences from the experiences indicate that the Cat-Ox system would probably be more desirable in an integrated system application rather than in a retrofit situation. The benefits associated with the integrated system application are:

- the reheat system would not be required,
- there could be more advantageous placement of system components and elimination of long product lines and poor accessibility of some equipment, and

- the annual operating costs would be lower for an integrated Cat-Ox.

TESTING RESULTS

The only testing completed at the Wood River site on an operational Cat-Ox was the 24-hour acceptance test which indicated that the system would meet design specifications. However, during the acceptance test the system did suffer from high pressure drops across the demister. This problem was probably caused by poor control of the internal burners which caused the evolution of soot and subsequent clogging of the mist eliminator packing. The results of this test and the experiences that followed indicated that a longer acceptance test for future demonstrations may be desirable.

Illinois Power Company and Monsanto Enviro-Chem personnel agreed that the acceptance tests did fulfill the performance guarantee. The data demonstrated that Cat-Ox could produce an acceptable strength acid while removing sufficient amounts of SO_2 from the flue gas to meet existing standards. The sulfuric acid mist in the exit gas was continually below the 1 mg (100 percent H_2SO_4)/ACF specified in the Monsanto Enviro-Chem performance guarantee.

In general, these tests indicated that Cat-Ox would indeed operate at its design capacity and specifications if the problems with the reheat burners could be corrected.

The remainder of tests were performed at a time prior to the construction of Cat-Ox or with Cat-Ox off-line and inoperable.

The major areas of testing included:

- Baseline testing (for the main and transient programs)
- ESP testing (a series of special ESP tests and the scheduled main test program)
- Corrosion testing, and
- Special ancillary tests.

The baseline tests for the main program and for the transient test program produced no surprising results. The most significant conclusion that could be drawn from this series of tests was that for future testing of FGD systems, baseline testing may not be required, or at least can be minimized to areas where theoretical or predictive models are not well defined.

The test also showed that continuous gas testing produced more repeatable results than manual sampling. The gas and particle data collected in most cases fit the theoretical predictions very well.

The proximate and ultimate analyses of the coal and the elemental analysis of pulverizer rejects, furnace bottom ash, and fly ash did not provide any specific pattern beyond the expected results. The elemental analyses are of special value, however, in that they provided the means for determining emission rates to the ambient atmosphere for a number of elements not usually examined in emission testing programs.

The ESP was the only portion of the Cat-Ox system which was continually operational and as a result was most thoroughly tested.

The results of the ESP tests (special ESP test, main test program and transient program tests) produced the following conclusions:

- The Cat-Ox ESP can meet the design specifications (outlet loading of 0.005 grains/SCF for an inlet loading of 1.5 grains/SCF).
- Low sulfur coal reduces collection efficiency.
- The reduction in collection efficiency is not necessarily proportional to sulfur content.
- The data indicated that "soak times" required to reach steady state conditions in an ESP after a fuel change may be on the order of five days in some cases.
- A reduction in load will reduce outlet loading if all other conditions are constant and the ESP had not previously reached its lowest output (i.e., if the ESP is designed for 0.005 gr/SCF or 99.6 percent efficiency and it reaches 0.005 gr/SCF then even if the load drops, the ESP would not necessarily reduce emissions below 0.005 gr/SCF).
- The effects of soot blowing on ESP performance are minimal but the process does seem to decrease collection efficiency.
- Non-uniform flow does exist across the Cat-Ox ESP and can affect collection efficiency.
- The ESP collection efficiency varies with particle size. The minimum collection efficiency for particle sizes between 5 and 0.05 μm seemed to be at about 0.1 μm in diameter.

As stated earlier, the results from the transient baseline tests produced no surprising results. The boiler showed no significant increase in gaseous emissions caused by transient circumstances.

No actual transient tests were performed on an operable Cat-Ox; however, a theoretical study on the effects of start-ups and load change on Cat-Ox acid strength did indicate that start-ups in particular could cause significant decrease in acid strengths and hence high corrosion rates if extra care were not taken to control flue gas flow and temperatures. The effects related to load changes were easier to control but were less significant.

In general, the results of the corrosion test program agreed with the observations made on Cat-Ox equipment. All test materials and components within the Cat-Ox system showed good corrosion resistance with the exception of those areas that were exposed to dilute acid, acid gases, or condensing flue gas.

In areas of acid exposure the stainless steel, Carpenter 20 cb-3, Inconel, Incoloy, Monel, Duriron, Uniloy, Hasteloy, and chemical lead samples had the best corrosion resistance. Of the samples tested in condensing flue gas and acid gas environments the two stainless steels and Carpenter 20 cb-3 showed the least base metal loss; however, the large-scale pitting found on these three samples might be more of a problem then the somewhat higher base metal loss of the other materials tested.

Other areas of investigation included gaseous stratification, NO_x formation in the ESP, material balances, and an examination of particle size versus element content. The details and results of these investigations are given in subsequent sections of this report; however, since most of this testing was preliminary, no results are reported in this summary.

The continuous monitoring system (monitoring NO_x, SO_2, THC, O_2, CO_2, temperature, pressure, and differential pressure) operated successfully throughout the program. The automated control and integrated sampling systems developed no major problems. The only desirable component that was not monitored in the system was particulate matter, since a reliable continuous particle monitoring instrument was not available. Discussion of the specific equipment utilized in the continuous monitoring system is detailed in the instrumentation section of this report.

CONCLUSION

While the Cat-Ox process would seem to be a technically viable process, it is not as comparably attractive as it was when the demonstration program was initiated. Hence, it was felt the benefit associated with continuation of the program could not justify the costly refurbishment of the system. The data seem to imply that any new applications of Cat-Ox might best be made as an integrated system rather than a retrofit system with external burners.

SECTION II

PROCESS DESCRIPTION

GENERAL

The Cat-Ox$^{\text{T.M.}*}$ flue gas desulfurization system controls SO_2 emission by catalytic oxidation of the SO_2 to SO_3. The SO_3 is then collected from the flue gas as sulfuric acid in an absorption tower.

The addition of the Cat-Ox system to The Illinois Power Company (IPC) Unit No. 4 boiler (100 MW) at the Wood River Station required the interruption of the exhaust flue gas flow at the entrance to the stack, diversion through the process, and return of the cleaned gas to the stack. Boiler operations and particle removal are independent of the rest of the Cat-Ox system, and can operate during Cat-Ox maintenance outages by virtue of a gas by-pass around the Cat-Ox system.

Key objectives of the Cat-Ox system were: (1) to remove 85 percent of the SO_2 from the flue gas, and (2) to remove essentially 100 percent of the particulate matter from the flue gas. The system is designed to achieve these objectives over the normal boiler load range.

The Cat-Ox system and boiler are schematically shown in Figure 3. The process consists of six basic steps which are described as follows:

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*Cat-Ox$^{\text{T.M.}}$ is a proprietary designation of Monsanto Company.

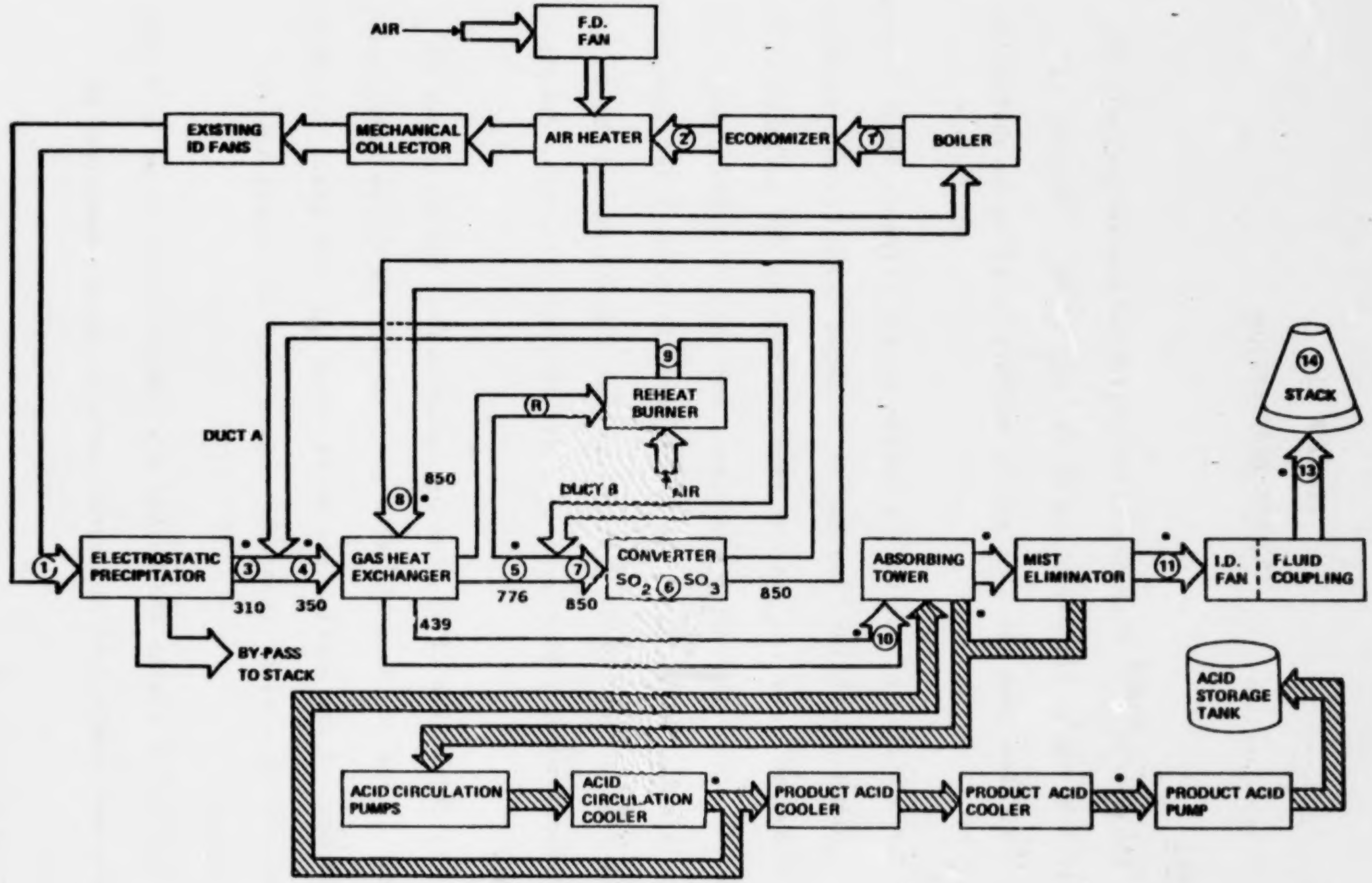
AIR
F.D. FAN
EXISTING ID FANS
MECHANICAL COLLECTOR
AIR HEATER
2
ECONOMIZER
1
BOILER
DUCT A
9
REHEAT BURNER
R
AIR
DUCT B
14
STACK
13
850
8
1
ELECTROSTATIC PRECIPITATOR
3
4
GAS HEAT EXCHANGER
5
7
CONVERTER
SO2 6 SO3
ABSORBING TOWER
MIST ELIMINATOR
11
I.D. FAN
FLUID COUPLING
310
350
776
850
850
439
10
BY-PASS TO STACK
ACID STORAGE TANK
ACID CIRCULATION PUMPS
ACID CIRCULATION COOLER
PRODUCT ACID COOLER
PRODUCT ACID COOLER
PRODUCT ACID PUMP

FIGURE 3. STEAM GENERATOR AND CAT-OX PROCESS

Flue Gas Cleaning

The flue gas leaving the existing I.D. fans on No. 4 unit flows to the Cat-Ox system. Rated design capacity of Cat-Ox for flue gas rate is 1,120,000 pounds per hour at 310°F and -0.5 inches w.c. The flue gas passes through an electrostatic precipitator which reduces the fly ash content of the gases from 1.5 grains/SCF to 0.005 grains/SCF. The precipitator is approximately 50 feet wide by 42 feet deep by 42 feet high and includes 16 hoppers for collection of fly ash.* The gas leaving the precipitator flows either through the SO_2 removal portion of the Cat-Ox process, or directly to the stack. Dampers and flues are arranged to permit this. Fly ash which is collected in the bottom hoppers on the precipitator is pneumatically conveyed to the existing fly ash disposal system.

Flue Gas Reheating

The cleaned flue gas from the precipitator flows through a Ljungstrom regenerative gas heat exchanger. The exchanger is 27 feet 6 inches in diameter and 8 feet high and includes facilities for water washing and soot blowing.

Prior to this step, an external oil-fired burner supplies heated recycle flue gas to raise the temperature from 310°F to 350°F. At full load, the heat input is 14.5×10^6 Btu/hr. The reheat burner is capable of operating on natural gas or #2 fuel oil. The reheated flue gas entry is located in the horizontal flue before the gas heat exchanger and is designated as reheat A.

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*A good portion of the work performed for this program was performed prior to the present EPA policy requiring the use of the metric system. Conversion of the data would be a lengthy task, hence, the data are presented in their original form and a conversion table is supplied in Appendix A.

Heating of the flue gas at this point is done to assure that no condensation takes place at the cold end of the gas heat exchanger. The flue gas is heated from 350°F to 776°F as it passes through the heat exchanger. Additional heated recycle flue gas is introduced downstream of the gas heat exchanger to bring the flue gas temperature to 850°F where conversion of SO_2 to SO_3 can take place. This reheat at full load heat capacity is 35.4×10^6 Btu/hr. The introduction point is located in the vertical flue downstream of the gas heat exchanger and is designated as reheat B.

Conversion of SO_2 to SO_3

With its temperature raised to that required for conversion, the flue gas passes through the converter where 90 percent of the SO_2 is catalytically oxidized to SO_3. This is accomplished using Monsanto's Cat-Ox A[*] catalyst. In the catalyst beds, the SO_2 is converted to SO_3 by exothermic reaction with oxygen in the flue gases as follows:

$$SO_2 + 1/2\ O_2 \longrightarrow SO_3$$

The heat generated by this reaction, approximately 1,319 Btu/lb sulfur, helps offset heat losses from equipment and flues. The converter is mounted directly above the gas heat exchanger and contains 8 beds of catalyst in parallel having a total length of 35 feet. Each bed is 12 1/2 inches deep and 30 feet by 30 feet square.

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[*] Registered trademark of Monsanto Company.

There is a gradual buildup of fly ash in the converter and, therefore, a gradual increase in pressure drop across the unit over a period of time. However, fly ash buildup has little effect on the conversion efficiency of the catalyst. When the pressure drop becomes excessive, cleaning of the catalyst is required. Equipment is provided to mechanically convey, clean, and return the catalyst to the converter with a minimal loss of material and no loss of activity. The expected frequency for catalyst cleaning is four times a year. To facilitate catalyst cleaning, a flue gas bypass is provided after the precipitator. Without affecting boiler operation, the SO_2 removal portion of the Cat-Ox system can be shutdown for cleaning.

Total downtime, including catalyst cool-off, cleaning, and heat-up is estimated at two days for the complete change of catalyst. It was estimated that approximately 2.5 percent of the catalyst volume must be added with each cleaning operation to replace losses due to screening and mechanical handling.

Heating Recovery

When the flue gas returns to the heat exchanger for temperature reduction, it is relatively rich in SO_3. Ninety percent of the SO_2 has been converted to SO_3 and it is at a temperature of 850°F.

Cooling is accomplished by the gas heat exchanger which heats untreated flue gas coming to the converter.

Seal leakage, typical of this kind of regenerative heater, will allow some of the cool SO_2 gas to bypass the heater and lowers the exit temperature at this point. Process design includes 5 percent leakage. The overall conversion of SO_2 entering the Cat-Ox system is 85.5 percent, accounting for this leakage.

Sulfuric Acid Absorbing System

The converter exit gas rich in SO_3 is partially cooled in the Ljungstrom regenerative gas heat exchanger and flows to the absorbing tower. The SO_3 gas produced in the converter, even though adequately cooled, will not combine directly with water in appreciable amounts but must be combined indirectly by dissolving it in circulating sulfuric acid in the packed section of the absorbing tower. Under this condition the SO_3 readily reacts with the water in the acid.

$$SO_3 + H_2O \longrightarrow H_2SO_4$$

The gas flows counter-current to the acid in the tower and is cooled to about 250°F. The sensible heat removed from the gas stream by the acid and the heat of absorption of SO_3 in the acid raise the circulating acid temperature in the two acid circulating pumps and is then pumped through the graphite tubular type acid coolers and returned to the top of the tower at the proper temperature. The temperature of the circulating acid is controlled by bypassing some of the hot acid around the coolers.

An acid level controller on the tower diverts a portion of the circulating acid through the product acid coolers. The product acid pump transfers the acid from these coolers to one of the two large storage tanks. The circulating acid pumps are rated at 1,000 GPM each. Sixty horsepower motors are provided with each pump. The entire circulating acid system is made of corrosion resistant materials. Product acid flow at full load is about 12 GPM.

All acid coolers are shell and tube heat exchangers. Water from the battery limits is pumped through the shell side and returned. The pressure of the cooling water is maintained above the pressure of the circulating acid to prevent leakage of acid into the water side of the cooler. The total flow rate of circulating acid on the tube side is monitored in the control room. System interlocks will bypass all flue gas from the boiler directly to the stack and shutdown the I.D. fan in the Cat-Ox system in the event of insufficient acid flow to the absorbing tower.

Miscellaneous spills from the acid pumps, coolers, or the absorbing tower are collected in an acid resistant pit, neutralized by periodic recirculation with soda ash, and pumped to the fly ash disposal area.

Very fine sulfuric acid mist is formed in the gas as it is cooled in the absorbing tower. These mist particles in the flue gas are removed along with some entrained droplets of circulating acid in the tower by a mist eliminator in the Cat-Ox system. This mist eliminator contains a first section, "S-C section," for particle removal and a second section, "H-V section," for mist removal. This highly efficient equipment was developed specifically for the Cat-Ox system and consists of fiber packed elements. The mist eliminators operate continuously and have no moving parts. Periodic washing of the mist eliminators is required because of particle buildup on the fibers. A semi-automatic wash solution system is provided to accomplish this.

The absorbing tower and the mist eliminators are contained within one vessel with approximate dimensions of 30 feet in diameter by 65 feet high.

The remaining piece of equipment, the I.D. fan, provides the motive force for the entire system. This fan is powered by two 2,500 horsepower motors. The flue gas is directed from the mist eliminators to the fan, and discharges to the existing stack for No. 4 unit. A variable speed fluid drive coupling is provided with the fan.

Product Storage and Loading

Cooled product acid at 60° Baume is collected in two 442,000 gallon steel storage tanks. An acid loading pump and tank car loading facilities are provided adjacent to the storage tanks. Tank trucks may also be loaded from this station if desired.

Instrumentation for the Cat-Ox system is fully compatible with the present No. 4 boiler instrumentation. Important process operating variables are transmitted to the control room for easy monitoring.

Alarms and interlocks are also provided to safeguard against boiler upsets due to operation of the Cat-Ox system. Normal operating ranges of important variables are indicated in Table 1.

TABLE 1. NORMAL OPERATING RANGE OF IMPORTANT VARIABLES IN THE CAT-OX SYSTEM

VARIABLE	VALUE
Flue Gas Temperature	**Temperature, °F**
Flue Gas to Gas Heat Exchanger	340-360
Flue Gas to Converter	825-875
SO_3 Gas to Absorbing Tower	420-440
Gas from Mist Eliminators	235-255
Acid Temperature	
Acid to Acid Circulation Coolers	275-290
Acid from Product Acid Coolers	70-110
Flue Gas Pressure	**Pressure, Inches w.c.**
SO_3 Gas from Converter*	-11 to -19
Gas from Mist Eliminator*	-41 to -53
Acid Flow	**Flow, GPM**
Acid to Absorbing Tower	1700-2100
Flue Gas Composition	**SO_2 PPM Volume**
Gas to Stack	300-400

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*Full Load

SECTION III

BACKGROUND AND GENERAL HISTORY

In 1969 Illinois Power Company initiated a study of the problem of sulfur dioxide released by the burning of Illinois coal to generate electricity. The Battelle Memorial Institute was employed to make a survey of research and development programs being conducted on sulfur dioxide removal systems. After intensive study, it appeared that the Cat-Ox system, following many years of research by the Monsanto Company, might be a feasible method and the system most nearly ready for a demonstration installation.

In 1962, Monsanto Co., Pennsylvania Electric Co., Air Preheater Co., and Research Cottrell Corp., started the pilot plant development of a FGD process based on catalytic oxidation of SO_2 followed by collection of sulfuric acid. The pilot plant proved the feasibility of the basic process operations would occur. The pilot plant handled a 400 SCFM slip stream from a pulverized coal fired boiler.

The next step in the development was a prototype plant using commercial size equipment. This unit handled 24,000 SCFM or approximately 6 percent of the flue gas from the No. 2 unit of Metropolitan Edison Company's Portland station. This unit received gas to the precipitator at 950°F directly from the boiler. This process flow is referred to as an integrated Cat-Ox System with no reheating of the flue gas being required. The unit was equivalent to about 15 MW of generating capacity.

Prototype plant operation began in August 1967 and finished in June 1970. The plant operated for over 8000 hours with the longest on-stream period of 30 days. The basic design and operating parameters were defined in this period. This then became the basis for design of a demonstration unit.

In early 1970, Illinois Power Company began negotiations with the Office of Air Programs of the U.S. Environmental Protection Agency (EPA) to jointly fund a demonstration unit on the 100 MW Unit No. 4 at the Wood River Power Station of IP. This project has been jointly funded by the EPA and by Illinois Power Company in an effort to advance the technology of sulfur dioxide removal by developing a system that would produce a usable by-product in the form of sulfuric acid.

Unit No. 4 at Wood River normally burned approximately 275,000 tons of coal per year with an average sulfur content of 3.1 percent. Based on these figures, the Cat-Ox system should produce about 25,000 tons per year of 78 percent concentration sulfuric acid.

Formal negotiations for installation of the Cat-Ox demonstation system were started with the preparation of a preliminary study by Monsanto Enviro-Chem in February 1970. The U.S. Environmental Protection Agency contracted with Illinois Power Company on 26 June 1970, to engage Monsanto Enviro-Chem to design and construct the Cat-Ox demonstration unit. Capital funding was shared approximately equally between the Environmental Protection Agency and Illinois

Power Company. In addition, Illinois Power Company assumed the financial obligations of providing the necessary utilities and of maintaining and operating the Cat-Ox system for a period identified in the contract.

Construction of the Cat-Ox system started in January 1971 and the associated Research-Cottrell precipitator designed for Cat-Ox was completed and placed in service in January 1972. Initial start-up of the sulfur removal equipment occurred on 4 September 1972, using natural gas for the in-line reheat burners. The system was operated for approximately 444 hours during the entire testing period. Because of the unavailability of natural gas, it was necessary to try to operate the in-line reheat burners on #2 fuel oil. In October 1972, testing with fuel oil was started. The testing period and modifications continued during the period of November 1972 to June 1973. During this test period, it became apparent that an external combustion chamber for reheating would be required to maintain satisfactory and continuous operation when using oil as the reheat fuel. This was necessary because the difficulty in achieving proper ignition of the in-line burners on #2 oil would cause excessive contamination of the catalyst. Also, these burners could not be maintained properly. Since this would not be acceptable, it was agreed to construct the external reheat burner using #2 fuel oil with the required heat being ducted into the system at the present location of the in-line burners.

Before installation of the external heater a performance guarantee test was run and satisfactorily completed using #2 oil as fuel in the in-line heaters in July 1973. The Cat-Ox operation that took place during this testing period increased the total operating time on the Cat-Ox system to approximately 602 hours. During the month of August 1973, the Cat-Ox system was deactivated and laid up in such a manner as to allow for a long outage so the external burner could be installed. The installation of the external burner was completed in April of 1974 and attempts were made to place the unit back in operation on 7 May 1974.

During this start-up a number of problems developed. They included a leak in the lead lining of the absorbing tower, the failure of the impellers in the acid circulation pumps, and leaks in the acid coolers. After extensive repairs and modifications, another attempt was made to place the unit in operation on 14 August 1974. But again in trying to get the system to operate, additional problems occurred and the system was shut down. Many additional attempts were made until finally it appeared that it would not be possible to continue to operate with the problems that existed. A lay up procedure provided by Monsanto was put into effect and the system was completely deactivated and laid up to protect the equipment from freeze or corrosion problems. This was completed in October of 1975.

ORIGINAL DEMONSTRATION PROGRAM SCHEDULE

Process Construction and Operation

The Cat-Ox program was divided into three phases. Phase I covered process design which includes the preparation of process requirements for equipment, piping, flues, instruments, electrical and insulation, flow diagrams, preliminary block plans and utility requirements. Also included in Phase I was a capital cost estimate to determine a guaranteed maximum price.

Phase II included the completion of detailed engineering, procurement of equipment, construction of the system and start-up operation.

Phase III was the data phase under which the Cat-Ox system was to be operated consistent with normal power plant operations for a minimum of one year following the completion of construction. All data relative to sulfur dioxide and fly ash removal and to sulfuric acid recovery during this period would be taken and made available for publication. In addition the EPA would have access to the same performance data information for a period of four years beyond the initial year of operation.

Proposed Time Schedule for the Program

Phase I was to be completed approximately four months from the effective date of the prime contract which was 26 June 1970. After the capital cost estimate was received by the U.S. government, there would be approximately thirty days allowed to audit the estimate and to secure approval.

The Phase II time schedule called for it to be completed 24 months after the effective date of the prime contract. Phase II would be deemed complete after successful completion of a performance guarantee test.

Phase III would include the operation of the Cat-Ox system for the one-year period.

Additional information regarding the Cat-Ox demonstration's chronological history is presented in Appendix B of this report.

Process Test And Evaluation

The test program for the Cat-Ox project ran coincident with the phases of the project:

Baseline Test Series (Phase I)

Acceptance Test Series (Phase II)

Main Test Program (Phase III).

The test programs performed during Phase I and scheduled for Phase III were tasked to METREK a division of The MITRE Corporation. The acceptance testing was completed by Monsanto and IPC.

Baseline Test Series

An operational test plan for the Cat-Ox demonstration program was developed for the planning, executing and analysis of the baseline measurements. The plan included (1) achievable objectives required by the total Cat-Ox demonstration; (2) background information on Illinois Power Company's Wood River Station Unit Number 4; (3) the requirements, scope, and description of the measurement program; (4) the requirements and plans for systematically sampling and analyzing flue gas and ancillary parameters; (5) a complete data management system; and (6) a coordinated set of responsibilities for joint participation by EPA, Illinois Power, The MITRE Corporation, and several sub-contractors.

The basic objectives of the test plan were fourfold: (1) define the relationship between the power unit's settings and operating conditions, (2) determine a baseline of performance for the unmodified steam generator unit, (3) test and calibrate various measurement systems for use during the Cat-Ox demonstration, (4) obtain quantitative data required for the establishment of realistic performance standards.

A complete description of the power unit was required in order to make a complete and comprehensive test plan. The description provided the various ranges of operating conditions and the associated control variables to be used during the test.

The general considerations used in designing the baseline measurements included required preparations for the test, uniformity of test conditions, duration to test runs, and instruments and methods of measurement. The scope of measurement included systems for fuel sampling and analysis, flue gas sampling and analysis, air and flue gas thermal structure, flue gas and air weight and humidity, refuse sampling and analysis, and efficiency calculations.

A complete flue gas sampling and analysis design was made to include both manual grab samples and continuous monitoring for purposes of comparison. Three flue gas sampling locations were selected to reflect various significant points in the combustion and stack areas of the plant. The design provided for selection procedures for instrumentation, grab sampling, and required chemical analysis of fuel, particulate matter and refuse. The selection procedure provided the necessary specifications required for sub-contracting of manual sampling and analytical services and purchase of measurement hardware.

In order to maintain quality control over the experiment a complete data management plan was developed to specify data control for sampling, analysis, reduction, and overall evaluation of the test program. Specifications were prepared showing the basic computations required to estimate the efficiencies of heat loss during the test.

Because the plan involved participation by various institutions, i.e., Illinois Power, MITRE, EPA, and sub-contractors, a definitive set of responsibilities was developed. This included the various interfacing between all participants and a schedule of milestones to be completed. The Baseline test program was completed and the results were reported in a MITRE Report M73-42 "Baseline Test Results."

The Acceptance Tests Series

As a final system acceptance requirement Monsanto Enviro-Chem performed a 24-hour performance guarantee test.

The performance factors of the Cat-Ox system which were to be quantified to satisfy the 24-hour performance guarantee period were defined as follows:

Monsanto Enviro-Chem will guarantee that the system will perform as follows based on a continuous operating test of 24 hours substantially consecutive duration:

1. The system shall be capable of operating with a gas flow of 1,120,000 pounds per hour entering the system at 310°F and 1.5 inches of water pressure. This defines the rated capacity of the system.
2. The system shall be capable of producing 60° Baume (77.7 percent H_2SO_4) sulfuric acid.
3. The exit gases emitted to the stack shall average to contain not more than 1.0 milligrams 100 percent sulfuric acid mist per actual cubic foot of gas when the system is operated at capacity.
4. The conversion of SO_2 to SO_3 in the gas reaching the converter shall be at least 90 percent at rated capacity.
5. The system shall operate so that over 99 percent of the fly ash contained in the flue gas leaving the boiler is removed, when the boiler is operating at rated capacity.
6. The system shall remove 85 percent of the SO_2 contained in the influent flue gas fed to the system.

The above performance guarantees were subject to the following conditions:

1. Monsanto Enviro-Chem Systems' engineering design and written operating instructions must be followed.
2. Fuel burned is as specified in the questionnaire containing data furnished by Illinois Power Company, dated 2 April 1970, and the flue gas to the system contains a maximum of 0.26 percent SO_2 and a minimum of 3.3 percent O_2, both by volume.
3. Flue gas temperature entering the converter is maintained between 830 and 900 degrees F.
4. Converter is loaded with the specified amount of Cat-Ox A catalyst.

Test description and discussions of the test run by Monsanto to satisfy these requirements are given in Section V.

One-Year Program Considerations

Whereas the 24-hour process performance guarantee test program was designed to satisfy contractual requirements, the one-year test program was to satisfy the definition of "adequate demonstration." Thus, the primary requirement of the program was that it be designed to quantify the factors defined as they relate to the criteria for adequate demonstration:

1. Operating characteristics and plant performance (relative especially to SO_2 and fly ash removals and to H_2SO_4 recovery).
2. Maintenance procedures, requirements, and costs.
3. Total process operating costs.
4. Longevity of the catalyst.
5. Catalyst susceptibility to poisons and to fly ash build-up; frequency and duration to necessary catalyst screening operations (and losses incurred thereby).
6. Necessity and frequency of mist eliminator washing operations.
7. Increase in seal leakage in the regenerative heat exchanger with time.
8. Corrosivity of all parts of the plant with time, especially in the acid loop and heat transfer equipment.
9. Marketability of the product sulfuric acid.

10. Response of the plant to fuels of varying sulfur content.

11. Effect of Cat-Ox System failure, if any, on power production.

12. Component pressure drops.

13. The ability of power plant personnel to operate and maintain the system.

In addition to this primary requirement, however, the one-year test program also considered all performance and economic factors which determine the ability of the Cat-Ox system to meet the criteria for adequate demonstration.

The overall demonstration program consisted of a Main Test Program (Steady State) and a Transient Test Program.

Briefly, the areas of testing were to be as follows:

- Main Test Program
    - Performance Measurements
        - Process Components
        - Overall Process
    - Availability/Reliability Studies
        - Process Components
        - Overall Process
    - Transient Test Program
        - Baseline (Normal Process Operation)
        - Simulated Malfunctions of a Mild Nature
        - Naturally Occurring Failures

Process and stack measurements were to be made by MITRE to assess these elements of process performance and to correlate results with emissions characteristics. Measurement support for the MITRE effort was provided in part by Midwest Research Institute (MRI). In turn, funding for this MRI effort was to be provided by the United States Environmental Protection Agency. Successful completion of the Test Program was the responsibility of The MITRE Corporation as agreed upon in contract with the Environmental Protection Agency and was contingent on successful operation of Cat-Ox.

Emission Characteristics of Interest--The Cat-Ox process is designed to desulfurize flue gas, but successful performance of the system requires particulate matter removal as well. Thus, sulfur oxides and particulate matter removal are a Cat-Ox design consideration and were monitored in both stack and process. Additionally, the Cat-Ox process generates significant quantities of sulphates (as SO_3 and sulfuric acid mist); careful monitoring for these emissions was also to be provided.

Finally, the concentrations of nitrogen oxides and total hydrocarbons were monitored. The Cat-Ox process is not designed for the removal and/or generation of nitrogen oxides and total hydrocarbons; however, several process components have the potential to affect the levels of these constituents (reheat burner, catalytic converter, gas absorber, etc.). Measurements were provided to assess the significance of these effects.

Test Program Elements--The Test Program required imposition of specified test conditions upon an electrical generating unit which is operated for profit. Thus, a series of objectives was established for both power-plant operation and the testing program to insure complete compatibility during periods of mutual activity. On this basis, the following objectives were defined for Illinois Power Company:

- Provide electric power in accordance with demand whenever possible.
- Insure atmospheric emissions from the boiler operation are in compliance with state and Federal standards for defined pollutants.
- Insure effluent discharges from facility operation are in compliance with state and Federal standards for defined pollutants at all times.

Similarly, MITRE Test Program objectives were defined as follows:

- Determine performance characteristics of the overall Cat-Ox process and its components when operated under design conditions.
- Assess Cat-Ox performance characteristics over extended periods of plant operation regarding:
  - Performance
  - Maintainability
  - Availability
  - Operating Costs
- Determine effects of Cat-Ox and Power Plant transient operating conditions on stack emission characteristics.

To meet these objectives the main Test Program Plan was developed, consisting of two phases: The Main (or Steady State) and the Transient Test Program. By carefully integrating both phases in developing this plan, each phase supported the other in providing information as the measurement program proceeded. Furthermore, the Main Program testing sequence was established statistically to reduce test program cost and to insure the maximum amount of nonrandomly biased data would be collected with the minimal amount of testing elements of the program are briefly outlined below, and details of these elements are provided in subsequent sections.

- Design Performance Testing (Main Program)
  - Process design basis was to be tested by process and stack measurements under boiler conditions that approximate the design basis (flue-gas composition and flow rate).
  - Measurements were to be made of the overall Cat-Ox process from electrostatic precipitator inlet to the stack, as well as several individual process components. Components whose performance relative to design were of particular interest were:
    - Electrostatic Precipitator
    - Reheat System
    - Catalytic Converter
    - Gas Absorber/Demister
- Process Maintainability (Main Program)
  - Characteristics of the process during actual operating conditions were to be measured. The same parameters as measured in the Design Performance Program were also to be measured in this program.
  - Evaluation of the Cat-Ox Process was to be made during a period of actual plant operation. Some deviations from design process input were expected and resultant Cat-Ox process performance measurements provide realistic evaluations of system behavior under all normally expected operating conditions.

- Reliability and Maintainability Evaluations (Main Program)
    - Evaluation of power-generation facility and Cat-Ox process interdependence and system integrity was to be made.
    - Examination of operating records, operator experience and detailed plant cost accounting was to provide information on Cat-Ox dependability with respect to both process performance and economic attractiveness (operating costs).
    - Economic evaluation was to be compared with original process estimates.
- Baseline Process Variations (Transient Program)
    - Normal operating transients which were planned during system operation were to be monitored. Events such as planned start-ups, shutdowns, and catalyst cleaning were included in this set.
    - Stack and process measurements were to be made during seven distinct modes of normally expected process transients.
- Simulated Malfunctions (Mod-1, Transient Program)
    - Transients which, after careful consideration and study, were established as likely to occur were to be simulated. Events which reduce Cat-Ox System Operation in a REVERSIBLE fashion were to be monitored. Four distinct simulations were planned for testing (with prior approval by Illinois Power Company officials).
    - Comprehensive process and stack measurements were to be made. Should an actual transient event occur prior or subsequent to the planned simulation (e.g., actual coal mill failure) the measurement program was to be initiated as rapidly as possible.
    - Simulated events were programmed after acceptable levels of operating experience had been secured.
- Natural disruptions in Process Operation
    - Transient events which were expected to seriously degrade Cat-Ox/Boiler operation were to be measured, if they occurred, and continued system operation was feasible.

- Under conditions such as a boiler-tube rupture wherein irreversible and sustained capacity reductions were expected, measurements were to be made for a period of time in which continuing operation was considered feasible. Prevention of permanent system damage and personnel safety were considered first priority for this element, however, and tracking of transient response was to proceed after these objectives were assured.

Program Integration--Priorities in scope, funding, and sponsor information requirements demanded the Main Test Program not include elements of the Transient Test Program. Thus, the transient program was to be conducted during those time periods not formally dedicated to the Main Test Program.

The Baseline (normal operation) phase of the Transient Test Program was conducted before and after completion of the Main Test Program activities (for example, start-up and shutdown measurements). As such, both instrumentation and personnel requirements are similar to the Main Test Program. However, with the Transient program, both manpower and instruments were to be dedicated for time periods that include the particular Main-Program test and the transient event.

During initial phases of the Main Test Program, only Baseline elements of the Transient Test were to be conducted until sufficient process operating test data were developed. Should mild malfunctions occur naturally during this time, simulation of the event would be deleted from that program, and/or the information would be used as adjunct data and/or to provide tolerable operating limits for future simulation tests.

To completely insure overall system integrity during the simulation phase, transients were to be simulated as a multiplicity of steady states. Wherever possible, variations of a given process parameter between two operating levels were to be performed in a step-wise incremental fashion to avoid irreversible system degradation. Each step was to be held until steady state was attained. This does not reflect the true transient step response; however, by providing measures of system performance at various operating levels, estimates could be made of the true dynamic response.

Scheduling of simulated mild malfunctions was done in such a fashion so that no measurements were planned during early Cat-Ox operation. A modest program of simulation was subsequently planned with tests of least possible impact on system integrity schedule first.

Subsequently, as the level of effort for the Main Test Program declined (all component tests completed), an increased level of transient simulation testing was planned.

Finally, no transients that offered a probability of permanent system degradation were to be simulated. Should a natural event of this nature occur, sustained measurements of system performance would have been made insofar as no damage to personnel and equipment was anticipated.

ACTUAL COURSE OF EVENTS

Process Construction and Modification

The following is a brief summary of the actual course of events during the construction and modification stage of the Cat-Ox system.

Phase I--Phase I, which was the design, engineering and cost estimate phase of this project, was completed on 26 October 1970. A design manual was issued containing processed design information along with necessary detailed design engineering and specification necessary to prepare the capital cost estimate. The capital cost estimate was reviewed by Illinois Power Company and the US EPA and the guaranteed maximum cost was accepted on 26 November 1970.

Phase II--Design, Construction and Start-up. Final design was started during Phase I and was essentially completed by 31 December 1971. Necessary drawings and specifications were prepared for the procurement and installation of all equipment, instruments, structures, foundation, electrical switchgear and other materials necessary for the Cat-Ox system. All equipment and major material items were purchased from this information.

The proposed installation using the Cat-Ox process was reviewed with the Illinois Environmental Protection Agency. The Illinois EPA issued a construction permit to Illinois Power Company on 20 April 1971 for the installation of the Cat-Ox system on Wood River Unit No. 4.

Field construction work started in March 1971 with the driving of piling. Piling installation was completed on 14 April 1971 and work was begun in early May on foundations.

The precipitator foundation concrete was poured on 28 May 1971, and by the end of June considerable precipitator support steel was in place and pre-assembly of the precipitator hoppers was well underway. Foundation rings for the acid storage tanks were beginning to be erected and foundations for the converter and gas heat exchanger were also poured during the month of June 1971.

By the end of July 1971 precipitator erection was proceeding well and was about 35 percent complete. Support steel for the gas heat exchanger and converter was delivered and erection was begun. Foundations for the acid storage tanks were complete.

At the end of August 1971, the precipitator erection was about 50 percent complete and the gas heat exchanger erection was about 10 percent complete.

By the end of September 1971, precipitator erection was about 75 percent complete, gas heat exchanger erection about 50 percent complete, and the acid storage tank erection, which was begun during the month, was about 50 percent complete. In the meantime, construction of electrical services to the battery limits by Illinois Power was underway and proceeding well.

As of 31 October 1971 the precipitator steel work was complete and the "tie-in" shutdown was planned to begin on November 13. Erection of the gas heat exchanger was approximately 98 percent complete, and four flue sections at the precipitator inlet were being put into place. The acid storage tanks were about 90 percent complete and the absorbing tower excavation was begun.

During November 1971 the overall erection of equipment was about 45 percent complete. The acid storage tanks were completed and successfully held water. The absorbing tower foundation and grillage were completed and the erection of the tower was begun. Also, erection of the converter was begun and flue erection continued with the inlet and outlet being put into place. Erection of the fly ash piping was approximately 45 percent completed.

During December 1971, the precipitator tie-in shutdown was started. Overall erection of equipment was about 55 percent complete. The absorbing tower shell erection was about 75 percent complete. Erection of the converter was continuing, about 25 percent complete. Precipitator insulation was about 95 percent complete. Electrical and piping work required for the precipitator was proceeding on schedule.

At the end of January 1972 precipitator tie-in was complete and was put into service on 28 January 1972.

An overall in depth review of the project schedule following the precipitator tie-in and start-up indicated that the construction completion and system start-up would be around 26 June 1972. This was a slippage in the schedule of about three weeks. The major factor causing this was the step-by-step construction of the absorbing tower lead lining, brick lining and internals. The absorbing tower shell and converter erection continued normally with a few working days lost due to bad weather. Both mist eliminator tube sheets were in place in the tower and installation of converter bed grating and screens was begun. Insulation of the precipitator was complete and the inlet flue to the precipitator was insulated and being covered with metal lagging.

During February 1972 excavation and forming of the remainder of the foundation was resumed. Pipe prefabrication and erection was continuing; electrical installation and plate work subcontractors were continuing their work.

In the month of March 1972 precipitator guaranteed performance tests were run. Preliminary results indicated the precipitor was meeting the guarantee. The Nooter Corporation completed work on the last of their equipment which included the absorbing tower and converter. Alberici Construction Company completed work on the gas heat exchanger and the majority of the flues and left the site. The lead lining and brick lining on the absorbing tower was started.

During April 1972 the lead lining work in the absorbing tower was completed and all foundation work was finished. Brick work, insulation and electrical work continued as did the piping and mechanical work. The induced draft fan assembly was started.

By the end of May 1972 the ID fan erection was about 80 percent complete. Brick work, insulation and electrical work were continuing and painting on the site was started. Also the catalyst handling system was completed and checkout of the equipment was started and the equipment placed into service. A start-up team composed generally of Monsanto Central Engineering Department personnel was assembled and was ready to begin some of the checkouts on equipment. After the checkout and start-up of the catalyst handling system, approximately 10,000 liters of Cat-Ox A catalyst was loaded into the storage bin, transferred into bed #8 of the converter, and then put back into the bin for storage. It was found that 1 percent of the catalyst was lost as fines during handling. An undetermined small amount was lost due to mishaps, spills and so forth. Generally, the system performed well and breakage of the catalyst was about as expected.

At the end of June 1972 mechanical and piping work was about 93 percent complete. Erection of the ID fan and the flue erection was completed. Also all brick work was essentially complete. Insulation, electrical work and painting continued during the month.

Almost all work was completed by the end of July 1972 with only a small amount of insulation and electrical work to be completed. With the advent of construction completion the start-up phase was begun. On 20 July 1972 the induced draft fan and hydraulic coupling was given an oil flush. On 24 July 1972, 66° Baumé (78 percent) sulfuric acid was unloaded from a railroad car and put to one of two acid storage tanks for future use.

All through the month of August, different systems and equipment associated with the Cat-Ox were checked out and placed into operation.

On 16 August 1972, the inlet duct blanking plate that separated the flue gas from the Cat-Ox system was removed leaving only the inlet damper to block the flow of flue gas to the Cat-Ox system.

On 17 August 1972, sulfuric acid was transferred from the acid storage tank to the absorbing tower and acid was circulated through the tower. The Cat-Ox outlet blanking plate was removed. On 18 August 1972, the loading of the catalyst into the converter was begun. The first attempt to light off the in-line furnace was tried on 27 August 1972. The first actual light off of the burners was accomplished on 29 August 1972 using natural gas as the fuel. On 30 August 1972 all of the catalysts had been loaded into the converter and all bins including the spare catalyst storage bin were full.

The start-up of the Cat-Ox system was scheduled for 2 September 1972, and the attempt was made. However, there were numerous problems that occurred during this period such as acid leaks and burner problems. But on 4 September 1972, a high enough temperature was achieved so that the by-pass damper could be closed and the Cat-Ox was actually on line for the first time with sulfuric acid being made.

On 5 September 1972 the Cat-Ox was continuing to operate on-line and sulfuric acid was transferred to the storage tanks to maintain the level in the absorbing tower; this acid strength was approximately 76.5 percent. During the period from 6 September through 19 September, the Cat-Ox system operated on a sporadic basis with the longest continuous run being the period from 13 September through 18 September. Numerous problems occurred during this period but some operation was able to take place on most of the days during that period. On 19 September a large severe acid leak occurred. The cause of the leak was a failure in a discharge expansion joint on one of the acid recirculation pumps. Because of the hot acid condition, the fumes and the amount of acid on the ground caused difficulty in getting into the area. The Cat-Ox was shutdown and extensive clean up operations were started in order to neutralize the acid and to make necessary repairs.

On 24 September the Cat-Ox system was started back up but again acid leaks required the system to be shutdown, and a maintenance program was put into effect to make the necessary leak repairs.

On 6 October 1972, the Cat-Ox system was started back up. During this period one of the acid recirculation pump bearings failed and that pump had to be taken out of service for maintenance.

During the period of 6 October through 14 October, the Cat-Ox was operated every day with some outages occurring during those periods.

During the period of 16 October through 30 October, the Cat-Ox system was out of service to make a number of modifications. Late on 30 October the Cat-Ox system was started back up and did operate on 31 October.

On 1 November 1972, the Coen representatives were trying to operate the B reheat burner and were having considerable difficulty. At that time it was decided to shut the Cat-Ox down for major burner repairs and testing of the burners on fuel oil. To do the burner testing on fuel oil, it was decided that the catalyst had to be completely removed from the converter and a number of the mist eliminators removed and others blanked off to protect them from the soot that would be developed during the testing of the burners using fuel oil.

During the period of 2 through 6 November, blanking plates were installed on the inlet and outlet. The absorbing tower was drained and washed down. On 6 November the process of removing the catalyst from the converter was started. By 15 November, all catalyst had been removed from the converter and was stored for later use.

During the latter part of November 1972, representatives from Coen Company were testing the use of fuel oil on both reheat burners. As a result of this burner testing, it was decided that considerable modification of the burners was required. So on 1 December 1972 a lay-up operation was put into practice to protect the Cat-Ox system from corrosion and freezing.

On 19 February 1973 representatives of the Coen Company and their contractors were on site to begin the burner modifications. On 22 March 1973, the Cat-Ox blanking plates were removed from the inlet and outlet ducts to provide for burner checkouts. Burner testing started on 23 March and continued through 26 March. On 1 April 1973, damage to the induced draft fan bearings and shaft occurred. This necessitated a shutdown from that period until 11 May to make repairs on the induced draft fan.

On 12 May 1973 testing of the burners was commenced again. The burner testing lasted through 25 May. On 29 May the loading of the catalyst back into the converter was begun and was completed on 2 June. During this time some broken tubes were found in the acid coolers, necessitating a maintenance program for repairing and plugging the tubes in the coolers.

On 6 May 1973 the reinstallation of the mist eliminators was begun. During this time 8 broken ceramic grid support bars were being replaced in the absorbing tower. On 18 May 1973 a mist eliminator wash procedure was put into operation to clean them as completely as possible. This was finished on 22 May. During this time, additional leaks developed in the acid piping and coolers and repairs had to be made. On 27 May an attempt was made to light off the burners and restore the Cat-Ox to operation.

During the period of 28 June through 3 July 1973, attempts were made to put the system into operation, but numerous acid leaks and other failures of equipment kept the Cat-Ox from actually operating to make acid.

On 5 July the blanking plates were installed in the inlet and outlet ducts and all acid pumped out of the absorbing tower, and the system opened up for washing and cleaning of the absorbing tower to make necessary repairs. On 20 July the system was prepared for operation and the Cat-Ox system was placed back into service. From the period 21 July through 29 July the Cat-Ox system was in operation each day. During the operation, there were instances when the burners were not operating. The mist eliminator washing was continuous through much of the test sequence. The 24-hour performance test was conducted during this sequence of operations. It began officially at 11:00 a.m. on 26 July. At 4:00 p.m. on 28 July the performance test was discontinued; however, the Cat-Ox system remained in service but at a reduced load. There were some times during the performance tests in which the reheat burners were not operating; however, it was Monsanto's contention that the 24-hour performance test was successful, and it was accepted.

During the period of 29 July to 1 August, the Cat-Ox system was continued in operation. However at 10:00 a.m. on 1 August, it was shutdown. On 2 August, the inlet blanking plate was installed and the procedure for taking the Cat-Ox system out of service for maintenance was performed. Through most of the month of August work proceeded to prepare the Cat-Ox system for a lengthy outage in order to install the new external burner system.

On 6 November 1973 removal of the in-duct reheat burners was started.

Modification of the Reheat System--During the period between 6 November 1973 to April 1974 the installation of an external combustion chamber progressed. This external combustion chamber was to provide the heat necessary to replace the two in-line burners of the original Cat-Ox design.

During January 1974 the installation of the external combustion chamber and equipment was in full swing. The A & B in-line reheat burners had been removed and the foundation and structural steel erected for the combustion chamber. All major items of equipment had been received and were on the site except for the recycle blower.

During March 1974 construction of the external combustion system was progressing satisfactorily and plans were being made for its start-up early in April.

Operation of the Cat-Ox System After Combustion Chamber Installation--On 8 April 1974, the pilot gas burner was lit off in the external combustion chamber, and a drying out process for the refractory in the combustion chamber was started shortly afterwards. On 15 April testing of the external combustion chamber using fuel oil was started. On 18 April an attempt was made to transfer acid to the absorbing tower, but it was found that the acid line was plugged and acid could not be transferred. This product acid line from the storage tanks to the absorbing tower was found to be plugged with solidified corrosion products, and necessitated cutting and flushing the line until cleared.

During the period from 2 May through 13 May a number of repairs to miscellaneous equipment were made including repair of acid line leaks, and leaks in the absorbing tower lead lining as well as repairs to the catalyst handling system so that additional catalysts could be added to the beds to top them off.

On 23 May 1974 repairs were started on the leaks in the absorbing tower using a potassium silicate solution.

On 3 June 1974 the blanking plates were removed and the Cat-Ox system prepared for start-up, with acid being added to the absorbing tower. On 4 June the external combustion system was placed into operation and on 5 June warming up of the Cat-Ox system was started. In the period from 7 June through 27 June 1974, attempts were made to circulate acid through the absorbing tower but acid cooler leaks, bearing failures in acid recirculation pumps, and broken impeller problems in the acid pumps caused shutdowns and resulted in considerable maintenance being done to these items during the entire period.

On 28 June the blanking plates were installed back in the inlet and outlet ducts. More leaks were found in one of the acid coolers and additional tube plugging in that cooler was required. On 10 July 1974 a piping change in the cooling water piping to and from the induced draft fan lube oil cooler was started. This was necessary to eliminate some of the temperature control problems of the oil from the lube oil cooler.

During the period of 29 July through 13 August 1974 the acid recirculation pumps were rebuilt and a new casing and impeller was installed on the product acid pump. Also additional tubes were plugged in one of the acid coolers.

On 14 August, all three acid pumps were operated for checkout and the blanking plates were pulled and the reheat burner system placed into operation. On 15 August, the reheat burner temperature was at 800°F, but there were problems in the air dampers on the reheat burner system. In the afternoon it was necessary to shutdown to repair a leak in the acid product line and to work on the dampers. The reheat burner system was placed back into service in the evening of 15 August and the temperature was held at 1050°F to dry out the combustion furnace. The operation of the reheat burner system was continued on 16 August, but a leak in the acid discharge header from the recirculation pump caused a shutdown about 5:50 p.m. and on 17 August, the blanking plates were reinstalled in the inlet and outlet ducts.

During the period of 17 August through 28 August, a number of repairs were made to the acid coolers and the acid recirculation system. On 17 September 1974 a masonry contractor removed damaged refractory brick from the combustion chamber of the reheat burner system. During the period of 17 September through 25 October substantial repairs were made to two of the acid coolers. On 25 October, a fire was lit in the reheat burner system to dry out the refractory in the combustion chamber. This drying out continued through 31 October and on into the first part of November. On 2 November 1974 the drying out of the reheat burner combustion chamber was completed and work was done on a new design connection at the transition point where the duct from the reheat burner system went into the reheat B area.

On 3 December 1974 a steam coil hot air heater was placed in service to keep moisture out of the catalyst beds. On 10 December 1974 a hydrostatic test was conducted on the product acid line to the storage tanks and during the period of 11, 12 and 13 December flushing and drying of the product acid line was done. During the rest of December and January 1975, only minor operations were conducted to test the ID fan. Meanwhile, work continued on the new design connection at the "B" transition.

On 28 January 1975 a small gas fire was placed in the reheat burner combustion chamber to dry out and cure the refractory. This continued through 30 January at which time the temperature was raised to 1800° to check out the combustion chamber. At this time testing the burner on the fuel oil was started. The testing of the combustion chamber on fuel oil continued through 3 February but difficulty was experienced with the gas pilot torch. Also on 3 February acid was transferred from the storage tanks to the absorbing tower to fill the cooler pumps and acid lines for tests. On 4 February all three acid recirculation pumps were run with no leaks observed. Reheat burner chamber checkout continued. On 6 February a tube leak occurred in the X04 acid cooler and it had to be isolated. On 7 February the reheat burner checkout continued with more reliability of the pilot being experienced. On 10 February the reheat burner was fired successfully several times but then difficulty occurred on the air/oil differential control. On 25 February acid was transferred back from storage in order to test the acid coolers and pumps. On 26 February the fuel oil fire was established in the reheat burner and the acid pumps were started up but leaks appeared in the acid coolers differential control. On 25 February acid was transferred back from storage in order to test the acid coolers and pumps. On 26 February the fuel oil fire was established in the reheat burner and the acid pumps were started up but leaks appeared in the acid coolers so the reheat burner was shutdown and the acid coolers drained.

During the period of 27 February through the end of March acid cooler work was continued and on several occasions the acid coolers were tested and additional leaks were found resulting in more repair work. On 8 April 1975 all acid from the north storage tank was pumped to the south acid storage tank. Also an attempt was made to pump acid from the absorbing tower back to the storage tank but difficulty was experienced in the product acid line.

At this point in time, Illinois Power requested that the costly attempts to repair Cat-Ox be stopped pending further agreement on how to proceed with the demonstration program. Toward this end EPA contracted Dow Chemical Company and Radian Corporation with support from MITRE/METREK to investigate the required means and costs to refurbish Cat-Ox as well as the costs and benefits of continuing the demonstration program.

On 12 May the product acid line was flushed with water and blown dry with air. On 14 August 1975 the catalyst from the #1 bed of the converter was conveyed to the storage tank in preparation for screening.

During the period of 7 August through 22 August, all of the catalyst was transferred through the sifter for cleaning purposes and replaced back in the beds. When it was completed, it was found that the #8 bed was down approximately ten feet. After an inspection it was found that large quantities of the catalyst had fallen down between the beds and into the gas spaces of the ducts. This area was cleaned and approximately 100 to 200 bushels of catalyst were removed from these spaces.

On 22 September 1975 the absorbing tower was opened up and the mist eliminator wash system placed into operation. The upper and lower mist eliminator tube sheets were completely washed down and all of the acid area of the absorbing tower was washed and cleaned.

Through the period of 29 September through 3 October, the Cat-Ox system was opened up for inspection by personnel of the Dow Chemical Company and MITRE Corporation.

On 17 October the Cat-Ox system was laid up and all cooling water systems drained for freeze protection.

In June of 1975 the Monsanto Enviro-Chem System, Inc., supplied the Illinois Power Company with a procedure for "mothballing" the Cat-Ox system. Illinois Power Company performed the necessary work to lay the Cat-Ox system up to prevent as much as possible corrosion and damage to the equipment as it sat idle.

STATUS OF PROCESS

The basic parameters of the Cat-Ox process were defined and have been sufficiently tested for confidence in design. However, the question still remains on the overall integration of this process into a power plant operation.

The demonstration unit built for the Wood River Station was a retrofit or reheat unit. The gas fired reheat Cat-Ox process has successfully met the performance guarantees at the 100 MW size, but needs to have a longer testing period to evaluate overall operability.

The oil-fired, in-line reheat system met the performance guarantees, but overall operation was not satisfactory with in-line burners. The oil fired system with an external burner was not successfully operated because of other equipment problems.

The concept of total integration of the Cat-Ox process with the boiler was tested in the prototype plant. The integrated unit with hot flue gas entering at 950°F has been tested for a longer period of time. Although operated successfully at 15 MW, this was a "slip stream." It remains to be demonstrated that the full output of a boiler could go through the Cat-Ox system without interfering with the boiler operation.

The process parameters for successful design and operation of a Cat-Ox system have been defined in the development to date. In specific areas, there is some further work needed on materials of construction. Additional work is needed on the integration of the Cat-Ox process into the control and operation of the boiler, particularly on start-up and shutdown.

CURRENT STATUS

Process Wood River Project

In June of 1975 Monsanto Enviro-Chem provided Illinois Power with a procedure for mothballing a Cat-Ox unit. As much as could be done, Illinois Power Company completed the lay up procedure on the Cat-Ox equipment. There was some equipment, because of its condition and its need for extensive maintenance or complete replacement, that kept it from getting the complete mothballing treatment.

During this inactive or mothballing stage there was some equipment that required periodic operation such as turning over of the induced draft fan and rotating the Ljungstrom air heater. In the process of operating the induced draft fan, a leak occurred in the lubricating oil system and the oil was lost from the system. Because of the extensive repairs that would be required, the fan is being left in the inactive state. The same type of situation occurred in regard to the Ljungstrom air heater. A periodic rotation of the air heater was performed, but a leak developed in the oil line for lubrication so it became necessary to stop the periodic operation of this piece of equipment also. It is felt that the non-operation of the air heater will not be any problem to it since there are periods of time in which the air heater can be left without operation and not cause any problems with the bearings or the air heater unit itself. In the case of the induced draft fan the condition of the bearings and the shaft on that fan are such that if it ever did become necessary to operate the unit extensive repairs would be required on the fan.

The major sections of the Cat-Ox system such as the two acid storage tanks and the absorbing tower have all been completely cleaned out and dried out so that there should not be any acceleration of corrosion in this equipment. The converter has been left with the catalyst in place, and there is a steam heated system supplying warm air into the converter to keep the catalyst dry. It would be difficult in making an evalutation of the Cat-Ox in its current stage to enumerate the condition of all of the equipment without becoming too detailed for this particular section of the report. There have been several evaluations made on the Cat-Ox system that do give detailed conditions of the equipment and if such detail is required then those reports should be consulted.

Process and Related Testing

The Baseline Test program was performed on schedule and as planned with no significant difficulties. The results of the test program are described in Section 5 of this document. Both the Test Plan and the Test Results were completed and published as MITRE Documents MTR-6053 and M73-42 respectively.

The Monsanto acceptance tests were also completed. These tests brought out some problems in the system (primarily with the internal burners) which were to be resolved prior to the start-up of the demonstration program. The test results are also discussed in section 5 of this report. IP and Monsanto agreed that the test series was acceptable proof that the system would operate.

The main test program was not completed since the Cat-Ox one year demonstration program could not be initiated because of the problems encountered. One portion of the test program was completed, it was the first series of ESP tests which are described in section 5. These tests comprised a series of subsystem (ESP) tests which did not require the operation of Cat-Ox. A number of Transient program tests were also performed. These tests were mainly baseline tests to determine the changes that occurred in emissions under normal start-ups and load changes in the boiler. These tests were also performed when Cat-Ox was not in operation.

A corrosion test program was performed at Cat-Ox. While most of the testing was completed under non-operational conditions, some testing was performed under start-up conditions. A study consisting of observations of equipment conditions was also part of the test program.

Official tests scheduled for the external burner were never run. However, MITRE did assist Monsanto and IP on some of the preliminary tests and obtained some initial data.

A comprehensive series of ESP tests was also performed and reported in Document No. EPA-600/2-75-037 of the Environmental Protection technology series. The report is summarized in Section V, "ESP Tests."

During the period of time in which the start-up of Cat-Ox was delayed, EPA expressed interest in MITRE performing a number of ancillary tests.

The tasks included:

1. Perform a photographic site survey and prepare a slide presentation showing the condition of Cat-Ox
2. Examine the effects of low sulfur coal on Unit 4 ESP performance
3. Examine the effect of non-uniform gas flow rate on ESP performance
4. Investigate correlations between particle size and trace metal content for fly-ash
5. Evaluate NO_x formation in the ESP
6. Perform material balances of SO_2, SO_3 sulfate and trace metals

7. Investigate gas stratification

Task 1 was completed and used to assist Dow Chemical personnel in their cost for assessment refurbishing of the Cat-Ox unit. The results were published in MITRE working paper WP-11262.

An informal work plan was established for items 2 through 7; however, due to limited resources, equipment, and personnel, only very low level and short-term testing was possible. Section V of this report outlines these areas and discusses efforts to investigate these problems.

Another subtask was a MITRE study on the effects of start-up and load changes on Cat-Ox Acid strength. The study results were published in MITRE Document M75-88.

Instrumentation System

The MITRE/METREK instrumentation system was completed prior to completion of the external burner and the first Cat-Ox start-up attempts. The major portion the instrumentation was operational until approximately two weeks before the site withdrawal was initiated.

The instrument system operated successfully during the ESP efficiency tests, the first series of the main test program tests, and all ancillary tests, transient tests, and burner tests.

The system was dismantled 25 October 1976 and returned to EPA at a later date. The complete description of the equipment and system is presented in Section IV of this report.

SECTION IV

GENERAL INSTRUMENTATION PHILOSOPHY

In evaluating the performance of a process as complex as Cat-Ox over a span of a year or more, the most desirable approach to measuring the various involved parameters is a totally automated instrumentation network that continuously records data in a computer-compatible format. An automated, continuous measuring system has several advantages. One advantage is to obtain real time results. Also, immediate availability of data provides an early check on performance of instrumentation so that necessary repairs can be made quickly, and data loss minimized. Installation of continuous measuring instrumentation is cost effective for measurement programs like the one year Cat-Ox measurement program. In this time frame the initial cost of the equipment purchased and installed is offset by reduced man power requirements during program duration. Also, when utilizing continuous recording instrumentation, there is a tremendous advantage to storing the information on magnetic tape so that it can be readily processed by computer. The process of transferring data from strip charts to punched cards is error prone and expensive in time and manpower when large quantities of data are involved.

Unfortunately, a totally automated, continuous measuring instrumentation system was impossible to design for the one-year Cat-Ox evaluation (demonstration) for the following reasons:

- Automatic instrumentation for measuring certain parameters (for example SO_3 concentrations in flue gas) did not exist.
- Certain instruments, although automatic in nature, were more suited for laboratory use rather than in situ.
- All instrumentation requires calibration, tune-ups, and repairs periodically. The time period between calibrations range from twice daily for some instruments, to months for others.

The solution to the above problems was solved by designing an automated system to measure as many of the desirable parameters as possible and supplementing it with a team of skilled personnel to take manual samples. By employing a team of manual sampling experts, the evaluation could be enhanced in two ways: a) gaps left by the instrumentation system could be filled, and b) a second source of data would be available for adding confidence to the accuracy of the automated instruments.

Along with the manual sampling team, a small independent staff of technicians would be available for the periodic repair, tune-up, and calibration of the automated instruments.

The combination of an automated instrumentation system, a manual sampling team, and a maintenance/calibration staff was considered the most cost effective, accurate and thorough means of obtaining data for an evaluation of the Cat-Ox process.

OVERALL SYSTEM DESIGN

The design for the evaluation of the Cat-Ox process performance included both manual and continuous measurement methods as stated in the previous section. As a rule continuous measurement techniques were used where acceptable instrumentation was available. Parameters of the greatest interest that could not be monitored by instrumentation were the measurement of SO_3 gas, H_2SO_4 mist, and particulate matter. In some cases it was desirable to employ both continuous and manual methods dependent on measurement location and the desired accuracy.

A summary of the parameters to be measured and the method used is shown in Table 2.

OVERALL CONTINUOUS MEASUREMENT SYSTEM

The overall continuous measurement system superimposed on the Cat-Ox process is shown in Figure 4.

The overall system is divided into 4 main subsystems: The continuous gas measurement subsystem, the time shared gas measuring subsystem, the flow measurement subsystem, and the data acquisition, recording and controlling subsystem. For clarity Figure 5 is a simplified block diagram showing the overall instrumentation network. Inputs to the major subsystems are identified as measurement points as shown in Figure 4.

Gas concentrations from the stack (Point 14) were measured continuously by the continuous gas measurement subsystem. This location was also measured periodically by the time shared gas measuring subsystem. During those time periods when both gas measuring subsystems were simultaneously sampling from the stack, a correlation between

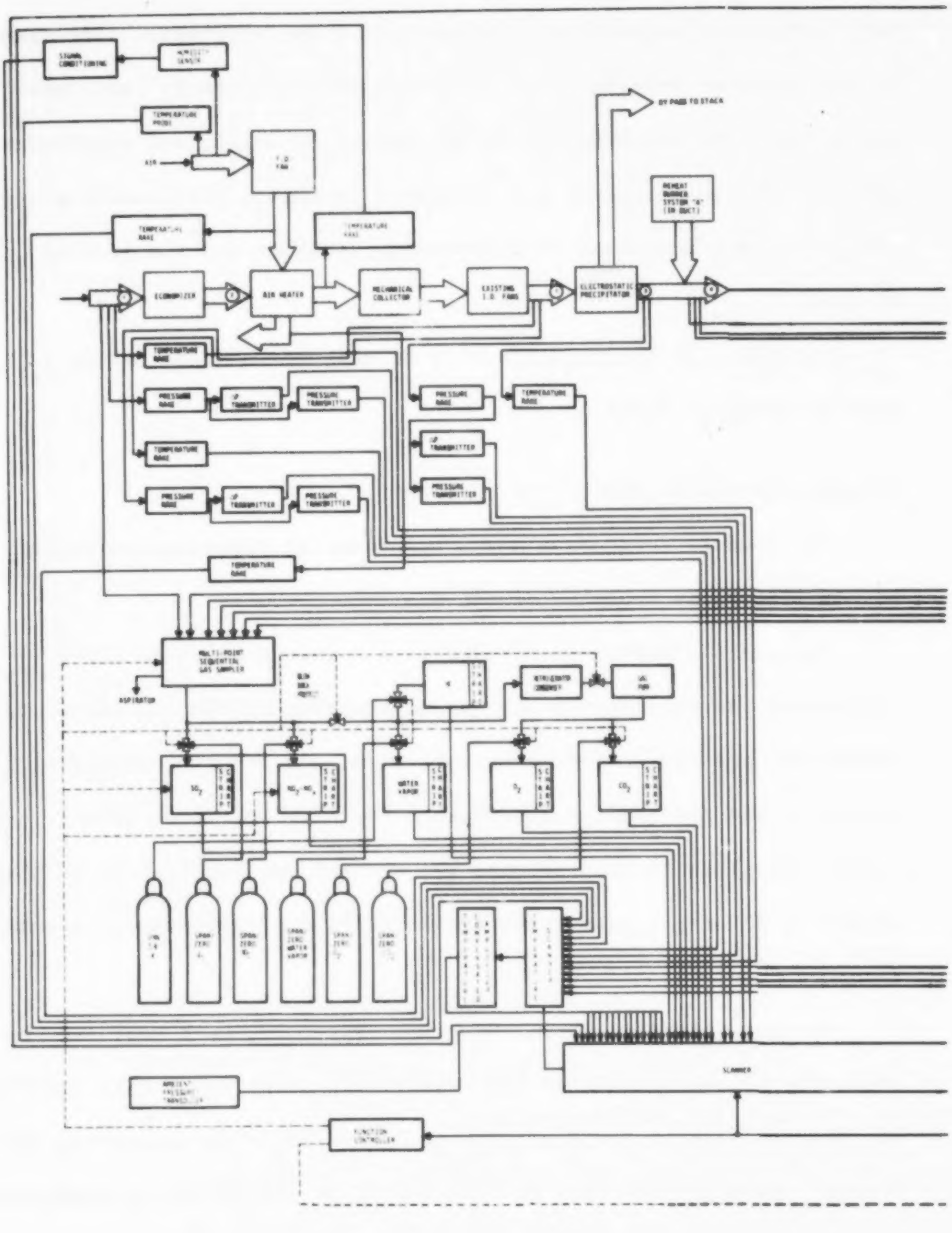
SIGNAL CONDITIONING
HUMIDITY SENSOR
TEMPERATURE PROBE
AIR
F.D. FAN
TEMPERATURE RAKE
TEMPERATURE RAKE
BY PASS TO STACK
REHEAT BURNER SYSTEM "A" (IN DUCT)
ECONOMIZER
AIR HEATER
MECHANICAL COLLECTOR
EXISTING I.D. FANS
ELECTROSTATIC PRECIPITATOR
TEMPERATURE RAKE
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
TEMPERATURE RAKE
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
PRESSURE RAKE
TEMPERATURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
TEMPERATURE RAKE
MULTI-POINT SEQUENTIAL GAS SAMPLER
ASPIRATOR
SO2
NO2-NOx
WATER VAPOR
O2
CO2
STRIP CHART
SPAN/ZERO
SPAN/ZERO
SPAN/ZERO WATER VAPOR
SPAN/ZERO
SPAN/ZERO
SCANNER
AMBIENT PRESSURE TRANSDUCER
FUNCTION CONTROLLER

FIGURE 4
CAT-OX INSTRUMENTATION SYSTEM

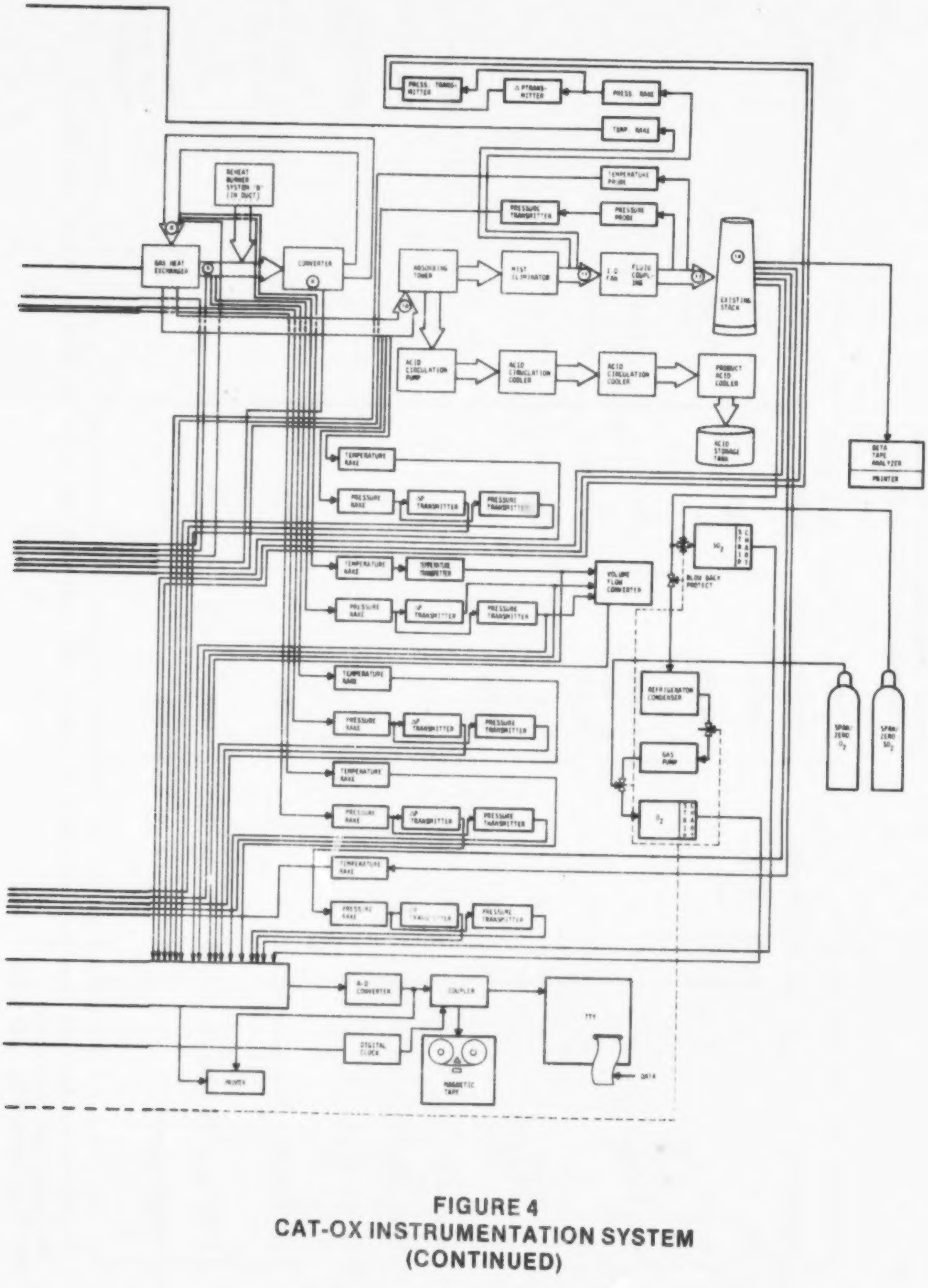
PRESS. TRANSMITTER
ΔP TRANSMITTER
PRESS. RAKE
TEMP. RAKE
REHEAT BURNER SYSTEM "B" (IN DUCT)
TEMPERATURE PROBE
PRESSURE TRANSMITTER
PRESSURE PROBE
GAS HEAT EXCHANGER
CONVERTER
ABSORBING TOWER
MIST ELIMINATOR
I.D. FAN
FLUID COUPLING
EXISTING STACK
ACID CIRCULATION PUMP
ACID CIRCULATION COOLER
ACID CIRCULATION COOLER
PRODUCT ACID COOLER
ACID STORAGE TANK
BETA TAPE ANALYZER
PRINTER
TEMPERATURE RAKE
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
TEMPERATURE RAKE
TEMPERATURE TRANSMITTER
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
VOLUME FLOW CONVERTER
SO_2
STRIP CHART
BLOW BACK PROTECT
REFRIGERATOR CONDENSER
GAS PUMP
O_2
STRIP CHART
SPAN/ ZERO O_2
SPAN/ ZERO SO_2
TEMPERATURE RAKE
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
TEMPERATURE RAKE
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
TEMPERATURE RAKE
PRESSURE RAKE
ΔP TRANSMITTER
PRESSURE TRANSMITTER
A-D CONVERTER
COUPLER
TTY
DIGITAL CLOCK
PRINTER
MAGNETIC TAPE
DATA

FIGURE 4
CAT-OX INSTRUMENTATION SYSTEM
(CONTINUED)

TABLE 2

CAT-OX DEMONSTRATION PROGRAM
INSTRUMENTATION SUMMARY

Parameter	C = Continuous M = Manual	Continuous Equipment Manufacturer	Continuous Equipment Model	Techniques	Manual Method
SO_2	C	DuPont	461C	UV Absorption	
NO_2/NO_x	C	DuPont		UV Absorption/ Oxidation	
Total Hydrocarbons	C	Beckman	400	Flame Ionization	
CO_2	C M	Bendix	UNOR-6	NDIR***	
H_2O Vapor	C M	MSA	LIRA M202	NDIR***	
O_2	C M	Beckman	F-3		
SO_3 Gas	M				EPA Method 8 Train
H_2SO_4 Mist	M				EPA Method 8 Train
Particulate	M				EPA Train (Plus In Stack Filter)
ΔP (Dynamic Pressure)*	C M	L&N**	1912		S Type Pitot and Inclined Draft Gauge
P (Static Pressure)	C M	L&N	1912		
Temperature*	C M	L&N	1992		Thermocouple and L&N Millivolt Standard

* Continuous in-duct temperature/pressure rakes were designed and built by United Sensor and Control
** Leeds and Northrup
*** Nondispersive Infrared

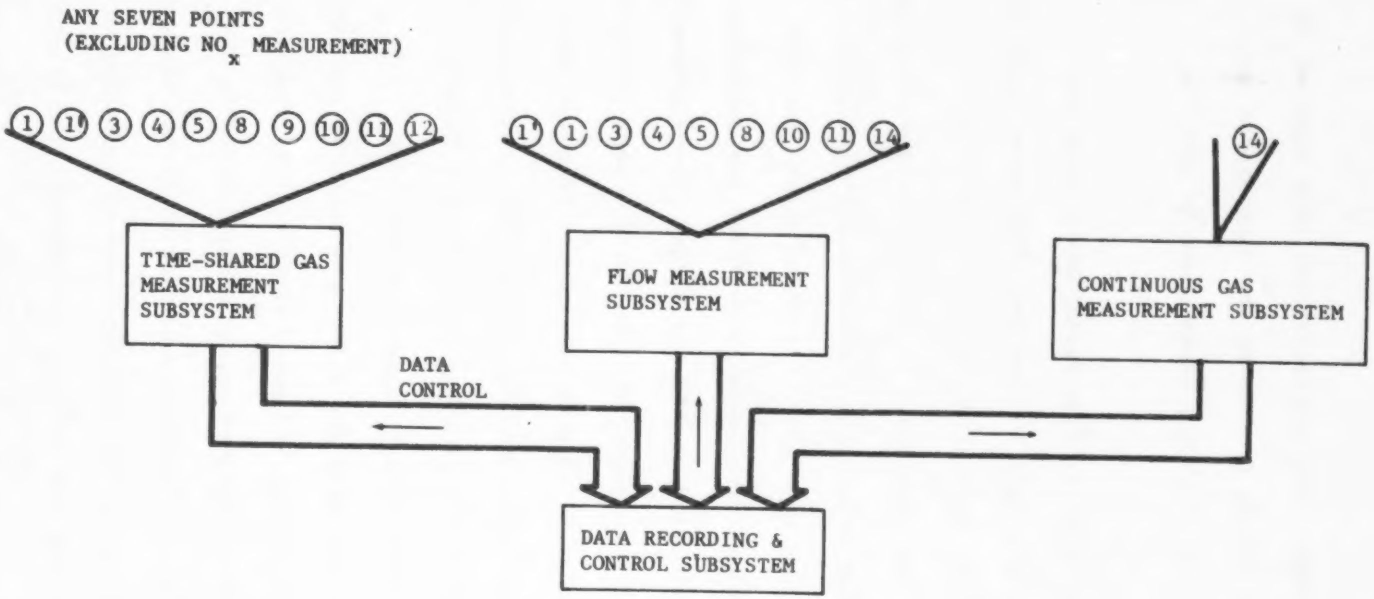
ANY SEVEN POINTS
(EXCLUDING NO_x MEASUREMENT)
1
1'
3
4
5
8
9
10
11
12
TIME-SHARED GAS MEASUREMENT SUBSYSTEM
DATA
CONTROL
1'
1
3
4
5
8
10
11
14
FLOW MEASUREMENT SUBSYSTEM
14
CONTINUOUS GAS MEASUREMENT SUBSYSTEM
DATA RECORDING & CONTROL SUBSYSTEM

FIGURE 5
MEASUREMENT POINT AND INSTRUMENTATION SYSTEM RELATIONSHIPS

the two systems would be made. Gas concentrations were measured at six other locations in the Cat-Ox process by the time-shared gas subsystem such that individual Cat-Ox process elements could be studied.

With the exception of Point 6, flow measurements were made wherever gas measurements were made so that mass flow rates could be computed. Flow measurements could not be made at Point 6 due to the limited access to that location. In addition to the locations where both gas and mass flow were made, there are several others where flow measurements alone were made. At those points the flow measurements could be combined with manually measured gas concentrations or used alone for the evaluation of individual Cat-Ox elements.

Data from the gas and flow measurement subsystems were automatically recorded on strip charts, by printers, and on magnetic tape. Strip chart and printer data were used for a real time assurance that the instrumentation was operating properly and also as a back-up data source in the event that magnetic tape data were lost. Data recorded on magnetic tape were used for subsequent computer processing, thus eliminating the tedious and error-prone task of transferring data from strip charts to punched cards. Synchronized to the data recording equipment was a function controller which was designed to perform certain automatic control functions such as switching of the time shared gas subsystem, gas analyzer calibration, and blowback of sampling lines.

Continuous Gas Measurement Subsystem

Figure 6 shows the flow diagram of the gas measurement subsystem which was designed to sample gas continuously from the midpoint of the stack. SO_2 and O_2 concentrations were measured by instrumentation located in an environmentally controlled building near the stack sample ports. Flue gas was drawn through a simple probe to a heated water trap and external filter. The gas was then conveyed to an SO_2 analyzer via an electrically heated teflon gas line (Dekoron line). Next, the gas passed through a refrigerator-condenser to remove water vapor. Finally, the flue gas was pumped through a sampling handling system into the O_2 analyzer. The refrigerator-condenser removed excessive water vapor which could cause corrosion of the O_2 analyzer sample cell.

Time Shared Gas Measurement Subsystem

Figure 7 shows the flow diagram of the time shared gas measurement subsystem. Flue gas is drawn to the analyzers through a filtered probe which was either an in-the-duct filter or an external heated filter. The gas from the probe was passed through heated traps and then through heated teflon gas lines (Dekoron lines). The gas lines were heated to prevent the condensation of water vapor and hydrocarbons.

Gas was sampled from seven different locations by a multipoint sequential sampler. The gas was aspirated through the seven lines continuously except during blowback. Each line was then selected

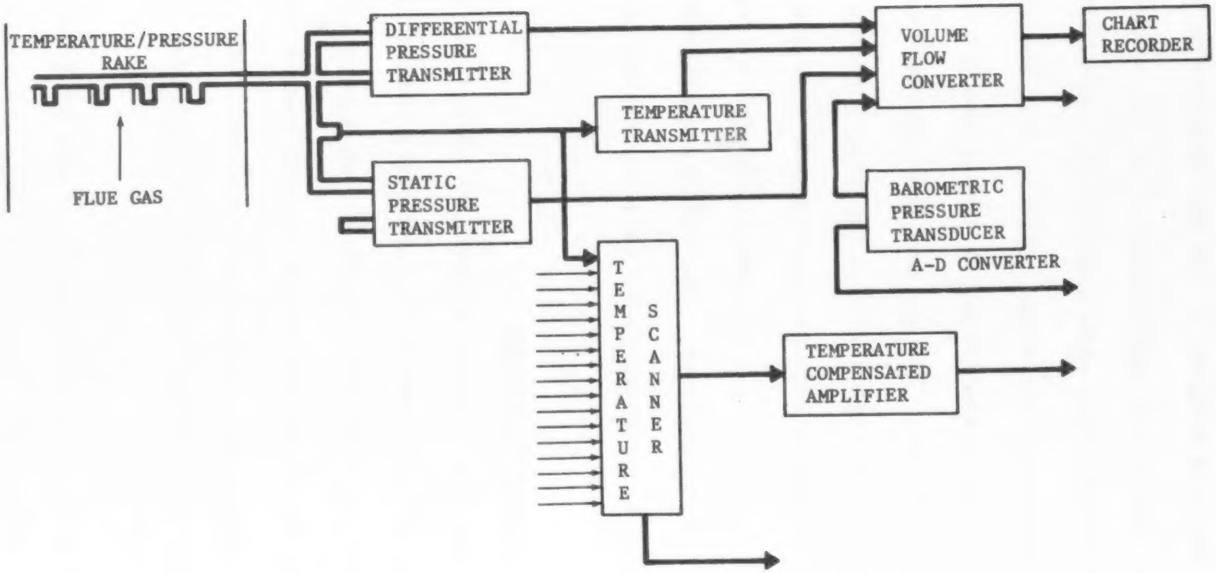
TEMPERATURE/PRESSURE RAKE
FLUE GAS
DIFFERENTIAL PRESSURE TRANSMITTER
STATIC PRESSURE TRANSMITTER
TEMPERATURE TRANSMITTER
VOLUME FLOW CONVERTER
CHART RECORDER
BAROMETRIC PRESSURE TRANSDUCER
A-D CONVERTER
TEMPERATURE SCANNER
TEMPERATURE COMPENSATED AMPLIFIER

FIGURE 6
FLOW MEASUREMENT SUBSYSTEM

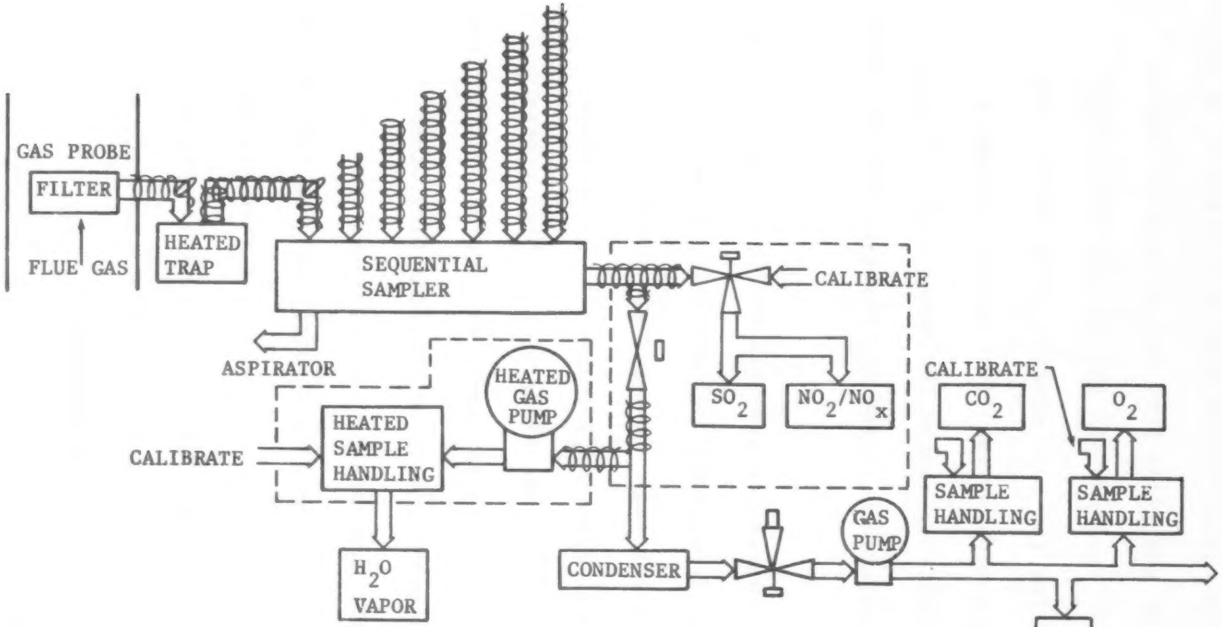
GAS PROBE
FILTER
FLUE GAS
HEATED TRAP
SEQUENTIAL SAMPLER
ASPIRATOR
CALIBRATE
HEATED SAMPLE HANDLING
HEATED GAS PUMP
H_2O VAPOR
CALIBRATE
SO_2
NO_2/NO_x
CONDENSER
GAS PUMP
CALIBRATE
CO_2
O_2
SAMPLE HANDLING
SAMPLE HANDLING
THC

FIGURE 7. TIME-SHARED GAS MEASUREMENT SUBSYSTEM

sequentially by switching pneumatic valves drawing a fraction of the gas into the analyzers. The gas lines from the sequential sampler to the combined SO_2 - NO/NO_2 analyzer and the THC and water vapor analysers were also heated for the same reasons given above. The flue gas to the CO_2 and O_2 analyzers was first passed through a refrigerator-condenser in order to remove the water vapor, thereby preventing water vapor interference in the CO_2 analyser and corrosion in the O_2 analyzer.

Operation of the time shared gas measurement subsystem is shown in Table 3. The subsystem is sequenced automatically on a one-hour time basis by the control subsystem. Flue gas was drawn into the analyzers from one particular line for a period of approximately 7 minutes, and then the same line was blown back by high pressure air for approximately one minute to to remove particulate matter from the ceramic filter. Subsequently, each of the remaining lines was sampled in succession in the same manner until the sequence was completed. Then, all of the analyzers were automatically zeroed against nitrogen (except for the SO_2- NO/NO_2 analyzer), and then spanned against a calibration gas. The SO_2- NO/NO_2 analyzer is provided with blowback air and is also designed to zero on the blowback air which is passed through the sample cells of the analyzer.

Flow Measurement Subsystem

The flow measurement subsystem is shown in Figure 8. Gas flow is determined by measuring differential pressure, static pressure,

TABLE 3. OPERATION OF TIME-SHARED SUBSYSTEM

POINT	OPERATION	TIME PERIOD MINUTES
1'	SAMPLE	7
	BLOWBACK	1
4	SAMPLE	7
	BLOWBACK	1
5	SAMPLE	7
	BLOWBACK	1
6	SAMPLE	7
	BLOWBACK	1
8	SAMPLE	7
	BLOWBACK	1
10	SAMPLE	7
	BLOWBACK	1
14	SAMPLE	7
	BLOWBACK	1
ALL ANALYZERS	ZERO	2
	SPAN	2
		60

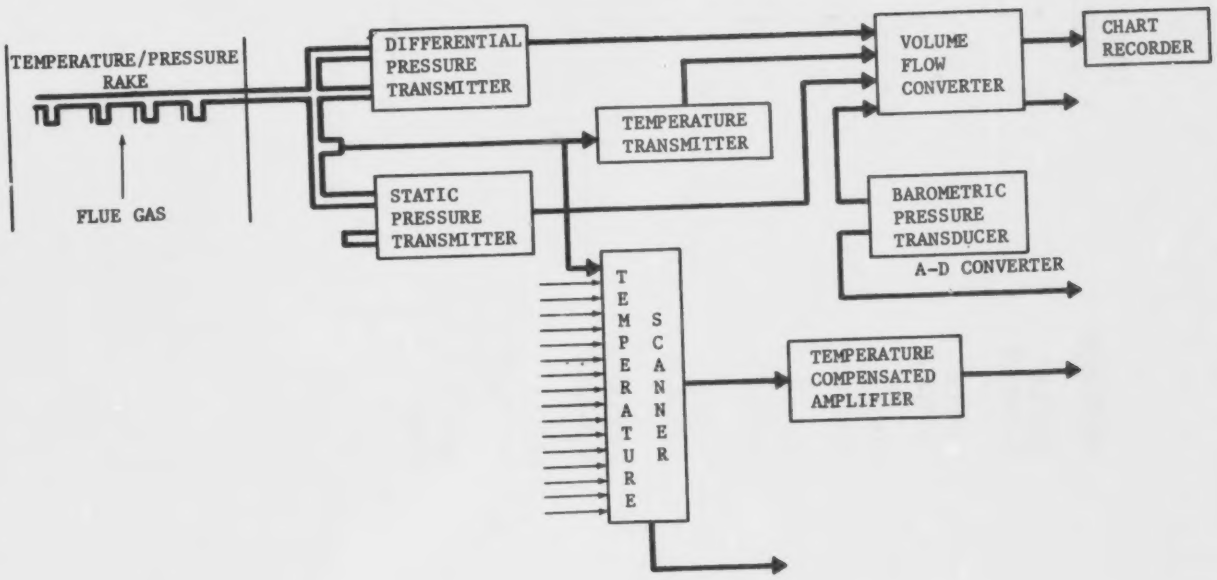
TEMPERATURE/PRESSURE
RAKE
FLUE GAS
DIFFERENTIAL
PRESSURE
TRANSMITTER
STATIC
PRESSURE
TRANSMITTER
TEMPERATURE
TRANSMITTER
TEMPERATURE SCANNER
VOLUME
FLOW
CONVERTER
CHART
RECORDER
BAROMETRIC
PRESSURE
TRANSDUCER
A-D CONVERTER
TEMPERATURE
COMPENSATED
AMPLIFIER

FIGURE 8
FLOW MEASUREMENT SUBSYSTEM

and temperatures which are combined in an analytical relationship to calculate flow. Since the cross-section of ducting is relatively large throughout the steam generator and Cat-Ox process, it was necessary to measure these parameters at a number of points within any particular duct in order to obtain a representative measurement. Therefore, the cross-section of the duct was divided into a number of sampling points based on the ASME power test codes, and an array of combined temperature/pressure rakes was used to sense differential pressure, static pressure, and temperature at the selected sampling points.

The magnitudes of the differential pressures and static pressures were measured by pressure transmitters and were normally recorded directly on strip charts and magnetic tape. Since temperature was measured at many more locations in the system than is required for flow measurements, the temperature sensors, which were iron-constantan thermocouples, were input through a constant temperature enclosure to a scanner. The scanner acted as a switch to connect thermocouples from various locations to a temperature-compensated amplifier which amplified, linearized, and temperature compensated the signal prior to entry into the analog to digital converter. The constant temperature enclosure maintained the connecter junctions at constant temperature so that voltages that were generated cancelled out.

In addition to recording the three parameters directly, a specialized analog computer identified as the volume flow control could be utilized at the output of any of the flow measurement instruments.

There were nine flow measurement locations which were nearly identical; however, at two of the locations, the economizer and the stack where differential pressures were particularly low, it was necessary to use an electronic manometer in place of the differential pressure transmitter.

Data Recording and Control Subsystem

The outputs of the analyzers, transmitters and other sensors were provided on magnetic tape as shown in Figure 9. The data acquisition system has a basic capacity of 50 channels which was expanded with an additional twenty channels by means of a low noise temperature scanner. Eight channels were assigned to gas concentration measurements, ten to static pressure, nine to differential pressure, one to gas volume flow, three to channel identification (of the sequential sampler) and ambient measurements, and fourteen spares (for use in the event additional data would be added).

Table 4 summarizes the discrete channel assignments as they were connected.

The scanner connected the analog signal from each channel in sequence to the analog to digital converter which "descretized" the analog signal. The data from the analog to digital converter

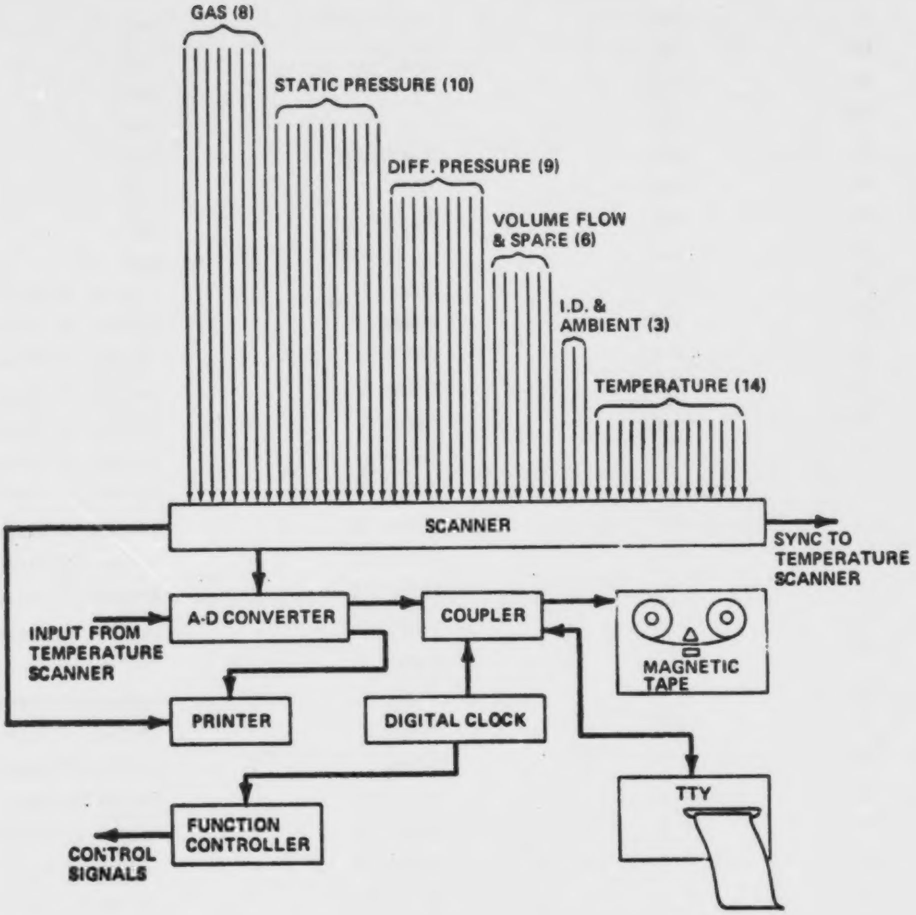
GAS (8)
STATIC PRESSURE (10)
DIFF. PRESSURE (9)
VOLUME FLOW & SPARE (6)
I.D. & AMBIENT (3)
TEMPERATURE (14)
SCANNER
SYNC TO TEMPERATURE SCANNER
A-D CONVERTER
COUPLER
MAGNETIC TAPE
INPUT FROM TEMPERATURE SCANNER
PRINTER
DIGITAL CLOCK
TTY
FUNCTION CONTROLLER
CONTROL SIGNALS

FIGURE 9

INFORMATION RECORDING FLOW CHART

TABLE 4. CHANNEL ASSIGNMENT DATA ACQUISITION SYSTEM

CHANNEL IDENTIFICATION	PARAMETER	LOCATION	UNITS
00	Gas	SO_2 (I.V.)	ppm
01	Gas	NO_2/NO_x	ppm
02	Gas	O_2 (I.V.)	ppm
03	Gas	CO_2	ppm
04	Gas	H_2O vapor	ppm
05	Gas	THC	ppm
06	Gas	SO_2 (R.S.)	ppm
07	Gas	O_2 (R.S.)	ppm
08	S.P.	Point 1'	Inches of Water
09	S.P.	Point 1	Inches of Water
10	S.P.	Point 3	Inches of Water
11	S.P.	Point 4	Inches of Water
12	S.P.	Point 5	Inches of Water
13	S.P.	Point 8	Inches of Water
14	S.P.	Point 10	Inches of Water
15	S.P.	Point 11	Inches of Water
16	S.P.	Point 13	Inches of Water
17	S.P.	Point 14	Inches of Water
18	Δ P	Point 1'	Inches of Water
19	Δ P	Point 1	Inches of Water
20	Δ P	Point 3	Inches of Water
21	Δ P	Point 4	Inches of Water
22	Δ P	Point 5	Inches of Water
23	Δ P	Point 8	Inches of Water
24	Δ P	Point 10	Inches of Water
25	Δ P	Point 11	Inches of Water
26	Δ P	Point 14	Inches of Water
27	Volume Flow	All Flow Locations	Inches of Water
28-32	Spare Channels		

TABLE 4. (Continued)

CHANNEL IDENTIFICATION	PARAMETER	LOCATION	UNITS
33	Channel Identification	N/A	V.D.C.
34	Barometric Pressure	I.V.	Inches Mercury
35	Relative Humidity	Input F.D. Fan	Percent
36*	Ambient Temperature	Input F.D. Fan	°Fahrenheit
37	Temperature	C.J. Reference	°Fahrenheit
38	Temperature	H_2O Trap, Point 1'	°Fahrenheit
39	Temperature	H_2O Trap, Point 4	°Fahrenheit
40	Temperature	H_2O Trap, Point 5	°Fahrenheit
41	Temperature	H_2O Trap, Point 6	°Fahrenheit
42	Temperature	H_2O Trap, Point 8	°Fahrenheit
43	Temperature	H_2O Trap, Point 10	°Fahrenheit
44	Temperature	H_2O Trap, Point 14 (I.V.)	°Fahrenheit
45	Temperature	H_2O Trap, Point 14 (R.S.)	°Fahrenheit
46	Temperature	H.L.I.V.	°Fahrenheit
47	Temperature	M.S.G.S. Output	°Fahrenheit
48	Temperature	Point 13	°Fahrenheit
49	Temperature	AHAI	°Fahrenheit
50	Temperature	AHAO	°Fahrenheit
51	Temperature	AHGI	°Fahrenheit
52	Temperature	AHGO	°Fahrenheit
53	Temperature	Point 1	°Fahrenheit
54	Temperature	Point 3	°Fahrenheit
55	Temperature	Point 4	°Fahrenheit
56	Temperature	Point 5	°Fahrenheit
57	Temperature	Point 8	°Fahrenheit
58	Temperature	Point 10	°Fahrenheit

---

*Channels 36-49 tentatively assigned depending on fabrication of signal conditioning.

TABLE 4. (Concluded)

CHANNEL IDENTIFICATION	PARAMETER	LOCATION	UNITS
59	Temperature	Point 11	°Fahrenheit
60	Temperature	Point 14	°Fahrenheit
61	Temperature	SO_2 (I.V.)	°Fahrenheit
62	Temperature	NO_2/NO_x	°Fahrenheit
63	Temperature	O_2 (I.V.)	°Fahrenheit
64	Temperature	CO_2	°Fahrenheit
65	Temperature	H_2O Vapor (L.R.)	°Fahrenheit
66	Temperature	H_2O Vapor (H.R.)	°Fahrenheit
67	Temperature	THC	°Fahrenheit
68	Temperature	SO_2 (R.S.)	°Fahrenheit
69	Temperature	O_2 (R.S.)	°Fahrenheit

LEGEND

I.V.	Instrumentation Van	H.L.I.V.	Heated Line Instrumentation Van
THC	Total Hydrocarbons	M.S.G.S.	Multi-Point Sequential Gas Sampler
R.S.	Roof Shed	AHAI	Air Heater Air In
S.P.	Static Pressure	AHGI	Air Heater Air Out
Δ P	Differential Pressure	AHGI	Air Heater Gas In
V.D.C.	Volts Direct Current	AHGO	Air Heater Gas Out
F.D.	Forced Draft	L.R.	Low Range
C.J.	Cold Junction	H.R.	High Range

were transmitted to the coupler to be put into proper format for recording on magnetic tape. A printer was utilized for the visual recording of selected data. In addition, a teletypewriter (TTY) was employed as an input/output device.

The scanner was normally operated at one scan per minute, but was capable of operating at better than one scan/5 seconds. The digital clock generated time in days, hours, and minutes, and provided a reference signal to the function controller. The function controller initiated start-stop commands to perform remote control functions such as sequencing of the time-shared gas measurement subsystem, calibration of the analyzers, and blowback of the probes.

INTEGRATED INSTRUMENTATION EVALUATION

Overall, the instrumentation system was reliable and comprehensive.

Time-sharing of the gas analyzers was a cost-effective and workable approach to measuring several gas concentrations from multiple locations. The system was very flexible and allowed a wide variation in test locations, times, and constituents. Portions of the system could be easily isolated to enable calibration or repair while the other portions of the system were operational. Though not totally an automated system the integrated system could easily function unattended for a period of hours freeing operators to perform manual sampling tests where required.

Use of low noise scanner to time-share the temperature measuring thermocouples was also a very good technique.

On refining the operation of the continuous measurement instrumentation the greatest emphasis should be placed on using instrumentation with long-term stability. Instrumentation that required frequent calibration was costly in manpower and tedious in its repetition. Evaluation of specific pieces of the test system is presented in Appendix C.

SECTION V

TESTING HISTORY

This section describes the results and conclusions determined from tests of Cat-Ox for support of the Cat-Ox system. All the tests described below are primarily emission related tests with the exception of the corrosion tests.

POLLUTION RELATED TESTING

Baseline Test Measurement Program

Test Objective--The objectives of the Baseline Measurement test were to determine the relationship between control settings and operating conditions for Unit No. 4 Steam generator and flue gas properties at the inlet of Cat-Ox plus characterize baseline performance in terms of operability, reliability and emission levels prior to installation of the process (Cat-Ox). These tests were also to test and calibrate measurement procedures to be used in the one-year test program. The quantitative data obtained could be used to support the establishment of realistic performance standards for emitted pollutants.

Test Schedule--A test program was developed which consisted of twenty-one separate tests, each of approximately ten hours duration. These twenty-one tests were conducted over a five-week period beginning 8 November 1971 and ending 9 December 1971.

Each of the twenty-one tests represented a particular combination of operating levels for the major steam generator parameters (load factor, fuel type, soot blowing, and excess air). The combinations of operating levels were selected so as to provide the maximum of information in a minimum number of tests, varying the parameters on a "one-at-a-time" basis.

Two supplementary gas traversal tests were also conducted to determine the pattern of leakage at the air heater (measurement position No. 2) and the gas flow pattern midway in the stack (measurement position No. 3).

A supplementary test was also conducted in which all factors were held constant except for burner angle, which was varied in steps from the minimum to maximum position.

For all of the tests, key steam generator operating parameters were monitored, samples of coal and ash were obtained at various points in the steam generator, gas samples were manually obtained, particle grain loadings were determined by manual sampling, and temperatures, pressures, gas flows, and gas concentrations were monitored by a MITRE designed continuous measurement system.

A summary of the Baseline test conditions is presented in Table 5. As indicated in the table, four load levels and four fuel options were examined in the tests. Two levels of soot blowing were investigated - no soot blowing and maximum soot blowing. However, in

TABLE 5

SUMMARY OF BASELINE TEST CONDITIONS

TEST NUMBER	DATE	LOAD FACTOR	FUEL** TYPE	SOOT BLOWER	EXCESS AIR
11	NOV 8	100 MW	A	NO	NORMAL
9	NOV 9	100 MW	A	NO	MINIMUM
8	NOV 10	100 MW	A	NO	MAXIMUM
12	NOV 11	100 MW	A	YES*	NORMAL
7	NOV 12	100 MW	A	YES	NORMAL
6	NOV 15-16	100 MW	B	NO	NORMAL
1	NOV 14-15	75 MW	B	NO	NORMAL
18	NOV 16-17	50 MW	B	NO	NORMAL
13	NOV 17-18	35 MW	B	NO	NORMAL
4	NOV 18-19	75 MW	A	NO	MINIMUM
5	NOV 21-22	75 MW	C	NO	NORMAL
10	NOV 22-23	100 MW	C	YES	NORMAL
20	NOV 23-24	50 MW	C	NO	NORMAL
2	NOV 29-30	75 MW	A	NO	NORMAL
3	NOV 30-DEC 1	75 MW	A	NO	MAXIMUM
17	DEC 1-2	50 MW	A	YES	NORMAL
19	DEC 2-3	50 MW	A	NO	MAXIMUM
21	DEC 3-4	35 MW	A	NO	NORMAL
14	DEC 6-7	50 MW	A	NO	NORMAL
15	DEC 7-8	50 MW	A	NO	MINIMUM
22	DEC 8-9	75 MW	D	NO	NORMAL

*Reduced level of soot blowing

**Type A → Peabody Coal = 2.7 lbs sulfur/10^6 Btu
Type B → Freeman Coal = 1.6 lbs sulfur/10^6 Btu
Type C → Mixture of Freeman and Natural Gas (≈1.0 lbs sulfur/10^6 Btu)
Type D → Metallurgical Coal = 1.0 lbs sulfur/10^6 Btu

one test early in the series, an intermediate level of soot blowing was examined.

Three levels of excess air were examined as shown in Table 5 - minimum excess air, normal excess air, and maximum excess air. The parameters measured at the sampling locations are presented in Table 6, while those that were connected with the boiler control are presented in Table 7.

Test Results--The results of the test program are presented in this section. A more detailed description of testing and analysis is presented in the report "Baseline Measurement Test Results for the Cat-Ox Demonstration Program" (EPA-R2-73-189).

Net and gross efficiencies were computed for all of the 21 tests in the Baseline Measurement Program and are presented in Table 8.

The efficiency calculations performed were basically those of the ASME publication PTC 4.1 using the heat loss method. Adjustments have been made, where required, based on the Illinois Power Company's computer performance calculations.

Gas mass flows and gas volume flows were computed for Location 1' (economizer) for SO_2, CO_2, O_2, N_2, and total gases. Mass flows and volume flows were also computed at Location 3 (midway in stack) for NO_2, CO_2, O_2, and N_2, and for total gases.

TABLE 6. BASELINE MEASUREMENT PARAMETERS (CONTINUOUS AND MANUAL MEASUREMENTS)

	CONTINUOUS MEASUREMENT SYSTEM	MANUAL MEASUREMENTS
LOCATION 1 (PRIOR TO ECONOMIZER)	O_2	SO_3
	SO_2	SO_2
	TEMPERATURE, AIR HEATER, AIR IN	NO_x
	TEMPERATURE, AIR HEATER, AIR OUT	CO
	TEMPERATURE, AIR HEATER, GAS IN	CO_2
	TEMPERATURE, AIR HEATER, GAS OUT	ORSAT O_2
	TEMPERATURE, AIR ENTERING FORCED DRAFT FAN	ORSAT CO_2
	HUMIDITY, AIR ENTERING FORCED DRAFT FAN	ORSAT CO
	PITOT TUBE ΔP STATIC PRESSURE FLUE GAS TEMPERATURE } GAS FLOW MEASUREMENT	
LOCATION 2 (BETWEEN UPPER AND LOWER TUBES OF AIR HEATER)	(NO CONTINUOUS MEASUREMENT AT THIS LOCATION)	GRAIN LOADING
		PARTICLE SIZE DISTRIBUTION
		ELEMENTAL ANALYSIS OF PARTICLES
		BOUND CONSTITUENTS ON PARTICLES
		PITOT TUBE ΔP STATIC PRESSURE FLUE GAS TEMPERATURE } GAS FLOW MEASUREMENT

TABLE 6 (CONCLUDED)

BASELINE MEASUREMENT PARAMETERS (CONTINUOUS AND MANUAL MEASUREMENTS)

	CONTINUOUS MEASUREMENT SYSTEM		MANUAL MEASUREMENTS	
LOCATION 3 (MIDWAY IN STACK)	PITOT TUBE ΔP STATIC PRESSURE FLUE GAS TEMPERATURE	GAS FLOW MEASUREMENT	SO_3 SO_2 NO_x	ORSAT O_2 ORSAT CO_2 ORSAT CO
	GRAIN LOADING		CO	H_g VAPOR
	SO_2		CO_2	
	NO_x		GRAIN LOADING	
	O_2		PARTICLE SIZE DISTRIBUTION	
	HYDROCARBON		ELEMENTAL ANALYSIS OF PARTICLES	
	CO		BOUND CONSTITUENTS ON PARTICLES	
	CO_2		PITOT TUBES ΔP STATIC PRESSURE FLUE GAS TEMPERATURE	GAS FLOW MEASUREMENT
OTHER LOCATIONS	(NO CONTINUOUS MEASUREMENTS AT OTHER LOCATIONS)		PROXIMATE & ULTIMATE ANALYSIS OF COAL	
			ELEMENTAL ANALYSIS OF COAL	
			ELEMENTAL ANALYSIS OF BOTTOM ASH	
			ELEMENTAL ANALYSIS OF AIR HEATER ASH	
			ELEMENTAL ANALYSIS OF MECHANICAL SEPARATOR ASH	
			PROXIMATE ANALYSIS OF PYRITE REJECTS	
			PROXIMATE ANALYSIS OF BOTTOM ASH	
			PROXIMATE ANALYSIS OF AIR HEATER ASH	
			PROXIMATE ANALYSIS OF MECHANICAL SEPARATOR ASH	
			ELEMENTAL ANALYSIS OF PYRITE REJECTS	

TABLE 7. BASELINE MEASUREMENT PARAMETERS
(STEAM GENERATOR GAUGE BOARD READINGS)

- CONDENSER VACUUM (PSI)
- ATM PRESS. AT AIR INTAKE (IN OF H_g)
- HUMIDITY AT AIR INTAKE (%)
- (INTEGRATOR LOG READINGS)
  - BOILER STEAM FLOW (LBS./HR.)
  - BOILER FW FLOW (LBS./HR.)
  - BEVEL GAS FLOW (LBS./HR.)
  - SH SPRAY FLOW (4TH FLOOR) (LBS./HR)
  - RH SPRAY FLOW (4TH FLOOR) (LBS./HR)
  - 'A' COAL SCALE (CLICKS)
  - 'B' COAL SCALE (CLICKS)
  - 'C' COAL SCALE (CLICKS)
  - 'D' COAL SCALE (CLICKS)
- (GAUGE BOARD READINGS)
  - (UTILITIES SECTION)
    - CONDENSER PRESSURE (IN OF H_g)
  - (FEEDWATER & STEAM SECTION)
    - DRUM PRESS (PSI)
    - D.C. HEATER PRESS (PSI)
    - 4A BFP DISCH (PSI)
    - 4B BFP DISCH (PSI)
    - BLR FEED HDR (PSI)
    - FW FLOW TO BLR (LBS./HR.)
    - MAINSTREAM TEMP (°F)
    - THROTTLE PRESSURE (PSI)
    - HOT REHT TEMP. (°F)
    - COLD REHT TEMP. (°F)
    - 4A RH SPRAY VALVE (%)
    - 4B RH SPRAY VALVE (%)
    - BURNER TILT (%)
    - 4A SH SPRAY VALVE (%)
    - 4B SH SPRAY VALVE (%)
  - AIR & FUEL SECTION
    - 4A FD FAN DISCH. (IN OF H_2O)
    - 4B FD FAN DISCH. (IN OF H_2O)
    - FURN. DRAFT (IN OF H_2O)
    - RHTR. OUTLET (IN OF H_2O)
    - SUPHTR OUTLET (IN OF H_2O)
    - ECON. OUT (IN OF H_2O)
    - 4A AIR HEATER OUT (IN OF H_2O)
    - 4B AIR HEATER OUT (IN OF H_2O)
    - 4A DUST COL. OUT (IN OF H_2O)
    - 4B DUST COL. OUT (IN OF H_2O)
    - STACK INLET (IN OF H_2O)
    - FLUE GAS O_2 (%)
    - STEAM FLOW (LBS./HR.)
    - AIR FLOW (LBS./HR.)
    - UNIT GROSS GEN. (MW)
    - AH 4A GAS OUT (°F)
    - AH 4B GAS OUT (°F)
    - 4A MILL (AMPS)
    - 4B MILL (AMPS)
    - 4C MILL (AMPS)
    - 4D MILL (AMPS)
    - 4A ID FAN (AMPS)
    - 4B ID FAN (AMPS)
    - 4A FD FAN (AMPS)
    - 4B FD FAN (AMPS)
    - 4A MILL FEEDER (%)
    - 4B MILL FEEDER (%)
    - 4C MILL FEEDER (%)
    - 4D MILL FEEDER (%)
    - GAS VALVE (%)
    - 4A ID FAN SPEED (RPM)
    - 4B ID FAN SPEED (RPM)
    - 4A ID FAN DAMPER (%)
    - 4B ID FAN DAMPER (%)
    - 4A FD FAN SHTOFF DAMP. (%)
    - 4B FD FAN SHTOFF DAMP. (%)
    - 4A FD FAN VANES (%)
    - 4B FD FAN VANES (%)
    - FUEL AIR RATIO SET PT. (%)

TABLE 8. NET AND GROSS EFFICIENCY

DATE	MITRE TEST NUMBER	TEST CONDITIONS					NET EFFICIENCY (%)	GROSS EFFICIENCY (%)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE		
11/8/71	11	100	A	NO	NORM.	NORM.	87.8	87.7
11/9/71	9	100	A	NO	MIN.	NORM.	88.6	88.6
11/10/71	8	100	A	NO	MAX.	NORM.	88.2	88.1
11/11/71	12	100	A	YES*	NORM.	NORM.	88.8	88.8
11/12/71	7	100	A	YES	NORM.	NORM.	88.9	88.9
11/15/71	1	75	B	NO	NORM.	NORM.	90.0	89.9
11/16/71	6	100	B	NO	NORM.	NORM.	89.9	89.8
11/17/71	18	50	B	YES	NORM.	NORM.	90.7	90.6
11/18/71	13	35	B	NO	NORM.	NORM.	90.8	90.7
11/19/71	4	75	A	NO	MIN.	NORM.	90.9	90.9
11/22/71	5	75	C	NO	NORM.	NORM.	88.8	88.7
11/23/71	10	100	C	YES	NORM.	NORM.	88.9	88.8
11/24/71	20	50	C	NO	NORM.	NORM.	88.5	88.4
11/30/71	2	75	A	NO	NORM.	NORM.	90.8	90.7
12/1/71	3	75	A	NO	MAX.	NORM.	91.0	90.7
12/2/71	17	50	A	YES	NORM.	NORM.	90.9	90.8
12/3/71	19	50	A	NO	MAX.	NORM.	89.0	88.9
12/4/71	21	35	A	NO	NORM.	NORM.	88.6	88.4
12/7/71	14	50	A	NO	NORM.	MIN.	88.1	88.0
12/8/71	15	50	A	NO	MIN.	NORM.	89.9	89.8
12/9/71	22	75	D	NO	NORM.	NORM.	90.7	90.7

* REDUCED LEVEL OF SOOT BLOWING

The flow rates for these gases at the two locations were based upon the results for the various measurement of mass and volume flow and presented in tabular form in Appendix D. The implications of the data are briefly discussed here.

The SO_2 flow rate at location 1' (stated in terms of mass flow - lbs per minute) appears to be consistent with the sulfur content of the fuel. The average mass flow for three 100 MW type A fuel tests (tests 8, 12, and 7) is 117.4 lbs/minute. The average sulfur content of the coal consumed in these three A fuel tests was 3.42 percent (on "as fired" dry basis). This average is greater than the 112.5 lbs per minute recorded for test 6, a 100 MW type B fuel test which consumed fuel with a 2.88 percent sulfur content. Both sets of tests in turn showed greater SO_2 mass flow than test 10, a 100 MW type C fuel test (simulated 1.08 percent sulfur fuel). In a similar comparison, the average SO_2 flow rate for three 75 MW type A fuel tests (tests 4, 2, and 3) is 84.8 lbs/minute. These three tests utilized coal of 3.32 percent average sulfur content. This average was approximately equal to the 75 MW type B fuel test (test 1) which utilized coal with an average sulfur content of 3.29 percent sulfur. Both the type A and B fuel tests showed a greater mass flow of SO_2 than the 75 MW type C fuel test (test 5) which utilized gas and coal to simulate a 0.86 percent sulfur coal. The 75 MW type D fuel test (test 22) produced an SO_2 mass flow that was higher than expected; however, the analysis of the coal consumed in this test showed it to be of 1.4 percent sulfur content rather than the expected 0.5 percent sulfur content. The SO_2 mass flow rates noted for this test were therefore consistent with this measured sulfur content. Similar relationships were found in the 50 MW tests with types A, B, and C levels. No significant changes in SO_2 mass flow were found which were traceable to changes in the soot blowing cycle or in excess air settings.

An examination of the mass flow of CO_2 at location 1' shows that for a fixed fuel type the CO_2 mass flow decreases with decreasing load levels (as would be expected with the reduced coal feed rates associated with the lower loads). The data also illustrate that, for a fixed load level, the CO_2 mass flow rates were not significantly different for fuel types A, B, and C.

Measurements of the O_2 flow rates at location 1' show that the O_2 mass flow rate decreases with decreasing load level, and, for a fixed load level, is not significantly different for fuel types A and B. Tests performed on C type fuel produced O_2 mass flow rates which were both greater and lower than the corresponding tests with A and B fuel dependent upon the load level. The greatest differences were found between tests with fixed load level and fixed fuel types where excess air was the varied parameter.

Flow rates for N_2 mass flow show that the N_2 mass flow rate decreases with decreasing load level, and for fixed load levels are not significantly different for fuel types A, B, and C. For fixed load levels and fixed fuel types, greater N_2 mass flow was found for the maximum excess air test.

The flow rates for total gas flow show the same relationships as the individual gases (i.e., same decrease with decreasing load level and same increase with increased excess air).

Tests performed on A type fuel at location 3 indicated NO mass flow rates were both greater and lower than the corresponding tests with B fuel dependent upon the load level. However, for all load levels, the NO flow rates with C fuel (predominantly natural gas) were significantly lower than the tests performed with A and B fuels.

The SO_2 flow rates measured at location 3 and relationships are similar to those noted for SO_2 at location 1', i.e., for a fixed fuel type the SO_2 mass flow is reduced for reduced load levels. Inconsistencies were found in the comparison between the 100 MW A fuel test (tests 8, 12, and 7) and the 100 MW B fuel test (test 6). Although the sulfur content was lower for the B fuel, the SO_2 mass flow measured on test 6 was greater than the average SO_2 mass flow for tests 8, 12, and 7. The results from test 10 did show the lower levels for SO_2 mass flow expected for a 100 MW C fuel test. The average SO_2 mass flow rate for the three 75 MW A fuel tests (tests 4, 2, and 3) is approximately equal to the mass flow for the 75 MW B fuel test (test 1); however, as was previously noted, the sulfur content of the coal consumed in these tests was approximately constant.

As was true of the measurements at location 1, the A and B fuel tests performed at the 75 MW load level produced higher SO_2 mass flows than measured in the 75 MW C fuel test. Similar relationships were found in the 50 MW tests with A, B, and C fuels.

The CO_2 flow rates measured at location 3 for fixed fuel types, show that the CO_2 mass flow decreases with decreasing load levels and that for a fixed load level, the CO_2 mass flow rates were not significantly different for fuel types A, B, and C.

The O_2 data collected at location 3 show that the O_2 mass flow rate decreases with decreasing load level and for a fixed load level is not significantly different for fuel types A and B. Tests performed with C fuel produced O_2 mass flows that were both greater and lower than the corresponding tests with A and B fuel dependent upon the load level. Differences were found in O_2 mass flow rate between tests at the 50 MW load level with type A fuel where excess air was varied (tests 19, 14, and 15). Similar differences were not found for 100 MW type A fuel tests where excess air was varied.

Flow rates for N_2 at location 3 illustrate that the N_2 mass flow rates decrease with decreasing load levels, and for fixed load levels are not significantly different for fuel types A, B, and C. For fixed load levels and fixed fuel types, greater N_2 flow was found for the maximum excess air tests.

The flow rates for all measured gases show the same relationships as shown for the individual gases (i.e., same decrease in flow rate with decreasing load level and same increase with increased excess air).

For each of the tests performed in the baseline program, the average coal consumption rate was determined utilizing the manual coal scale readings. The average sulfur content of the coal (as determined by chemical analysis) was then used with the coal scale readings to determine the rate of sulfur fed to the steam generator. Average SO_2 mass flow readings from the continuous instrumentation system at the stack were then used to determine the average sulfur flow at the stack:

Where,

$$\frac{\text{lbs sulfur}}{\text{minute}} = \frac{\text{lbs } SO_2}{\text{minute}} \times \frac{\text{molecular weight sulfur}}{\text{molecular weight } SO_2} = \frac{\text{lbs } SO_2}{\text{minute}} \times .50$$

The rate of sulfur feed into the steam generator was then compared with the rate of sulfur flow through the stack.

The results of the sulfur balance calculations are summarized in Table 9. These results are based upon measurement of the SO_2 concentration of the stack gas with the exception of test 15 in which SO_2 concentrations measured at location 1 (economizer) were corrected using estimated system leakage values to provide an estimate of SO_2 concentration in the stack. In all cases, the measurements of SO_2 concentrations do not include measurement of the sulfur exhausted from the stack as SO_3 or the sulfur adsorbed on the ash as SO_2 and SO_3. The results provided in Table 35 show good agreement on

TABLE 9. SULFUR BALANCE

DATE	MITRE TEST NO.	LOAD (MW)	FUEL	SOOT BLOWER	EXCESS AIR	BURNER ANGLE	AVERAGE COAL FLOW(1) (10^3 LB/HR)	% SULFUR IN COAL(2)	AVERAGE SULFUR FEED (LB/HR)	AVERAGE SULFUR FEED (LB/MIN)	AVERAGE SO_2 FLOW(3) (LB/MIN)	AVERAGE SULFUR FLOW (LB/MIN)	SULFUR FEED-FLOW (LB/MIN)
11/8/71	11	100	A	NO	NORM	NORM	85.0	3.37	2865	47.7			
11/9/71	9	100	A	NO	MIN	NORM	83.5	3.40	2839	47.3			
11/10/71	8	100	A	NO	MAX	NORM	63.7	3.37	2147	35.8	63.5	31.8	4.0
11/11/71	12	100	A	YES*	NORM	NORM	83.9	3.24	2718	45.3	77.9	39.0	6.3
11/12/71	7	100	A	YES	NORM	NORM	84.2	3.28	2762	46.0	91.0	45.5	0.5
11/15/71	1	75	B	NO	NORM	NORM	64.8	3.16	2048	34.1	69.0	34.5	-0.4
11/16/71	6	100	B	NO	NORM	NORM	90.1	2.76	2514	41.9	87.1	43.6	-1.7
11/17/71	18	50	B	YES	NORM	NORM	48.3	2.57	1241	20.7	35.7	17.9	2.8
11/18/71	13	35	B	NO	NORM	NORM	32.3	2.51	811	13.5	26.2	13.1	0.4
11/19/71	4	75	A	NO	MIN	NORM	63.2	3.37	2130	35.5	70.2	35.1	0.4
11/22/71	5	75	C	NO	NORM	NORM	34.0	1.83	622	10.4	20.0	10.0	0.4
11/23/71	10	100	C	YES	NORM	NORM	46.4	1.65	766	12.8	22.5	11.3	1.5
11/24/71	20	50	C	NO	NORM	NORM	26.0	1.68	437	7.3	12.5	6.3	1.0
11/30/71	2	75	A	NO	NORM	NORM	66.2	2.87	1900	31.7	52.9	26.5	5.2
12/1/71	3	75	A	NO	MAX	NORM	65.2	3.31	2158	36.0	69.3	34.7	1.3
12/2/71	17	50	A	YES	NORM	NORM	45.4	3.46	1571	26.2	43.5	21.8	4.4
12/3/71	19	50	A	NO	MAX	NORM	50.5	3.47	1752	29.2	45.7	22.9	6.3
12/4/71	21	35	A	NO	NORM	NORM	32.4	3.09	1001	16.7	31.4	15.7	1.0
12/7/71	14	50	A	NO	NORM	MIN	47.0	2.74	1288	21.5	39.6	19.8	1.7
12/8/71	15	50	A	NO	MIN	NORM	46.3	3.37	1560	26.0	46.6**	23.3**	2.7
12/9/71	22	75	D	NO	NORM	NORM	63.2	1.33	841	14.0	24.2	12.1	1.9

* Reduced level of soot blowing
** Location 1

(1) Coal Scale Measurement
(2) Midwest & IGS Average
(3) MITRE Measurement at Location 3

the sulfur balance leading to the conclusion that the total combined error in SO_2 and gas flow measurements was low. As noted in Table 9, in all cases except two (tests 1 and 6), the sulfur feed rate exceeded the sulfur flow rate measured in the stack indicating that there were, in fact, small unmeasured losses of sulfur.

Grain loadings were determined at location 2 and location 3 for all tests by means of manual measurements. These manual measurements were taken by the Midwest Research Institute using the sampling train and the operating techniques specified in the Federal Register of 23 December 1971 (Volume 36, Number 247).

A summary of the grain loading results is provided in Table 10. The emission rates shown in Table 10 were computed using the measured grain loadings and the manually determined gas mass flow with the appropriate conversion factors to provide values in terms of pounds of particulate matter per hour.

The mechanical collection efficiencies shown in Table 10 were calculated using the emission rates for the two locations (location 2 prior to collection and location 3 after collection). Because of the configuration of the ducting, this collection efficiency reflects an ash removal capability that is a result, not only of the effects of the mechanical collector proper but, also, of the lower tubes of the air heater, and the ducting between the air heater and the stack. For this reason, the efficiencies shown are not absolute values but are to be considered as relative measurements to be used only in

TABLE 10. GRAIN LOADING MEASUREMENTS

DATE	MITRE TEST NO. (OLD)	LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	AIR BURNER ANGLE	GRAIN LOADING				EMISSION RATE LB/HR.		MECHANICAL COLLECTOR EFFICIENCY (%)	ASH CONTENT OF COAL
							GRAINS/SCF		GRAINS/ACF					
							LOCATION 2	LOCATION 3	LOCATION 2	LOCATION 3	LOCATION 2	LOCATION 3		AS RECEIVED BASIS
11/8/71	11	100	A	NO	NORM.	NORM.	4.15	0.95	2.42	0.61	9128	—	—	10.03
11/9/71	9	100	A	NO	MIN.	NORM.	4.58	0.88	2.64	0.58	8460	—	—	9.89
11/10/71	8	100	A	NO	MAX.	NORM.	4.41	0.94	2.55	0.60	9796	2166	77.8	10.25
11/11/71	12	100	A	YES*	NORM.	NORM.	4.25	1.16	2.44	0.75	8252	2474	70.0	10.75
11/12/71	7	100	A	YES	NORM.	NORM.	5.09 5.38	1.44 1.50	2.94 2.96	0.91 0.93	10596	3104	70.5	10.07
11/16/71	6	100	B	NO	NORM.	NORM.	4.48	1.34	2.49	0.85	9808	2930	70.0	11.30
11/15/71	1	75	B	NO	NORM.	NORM.	5.58	1.08	3.14	0.68	8990	1856	79.5	10.42
11/17/71	18	50	B	YES	NORM.	NORM.	7.80 9.70	1.50 1.42	4.57 5.67	0.98 0.93	9830	1672	83.0	12.15
11/18/71	13	35	B	NO	NORM.	NORM.	3.79	1.00	2.30	0.68	3408	926	72.9	13.13
11/19/71	4	75	A	NO	MIN.	NORM.	4.27	0.66	2.45	0.43	6176	1072	82.7	10.35
11/22/71	5	75	C	NO	NORM.	NORM.	3.23	0.89	1.89	0.59	4978	1335	73.2	13.57
11/23/71	10	100	C	YES	NORM.	NORM.	5.71 6.12	1.24 1.38	3.23 3.49	0.78 0.90	11160	2573	76.9	16.69
11/24/71	20	50	C	NO	NORM.	NORM.	3.63	1.12	2.20	0.76	3676	1164	68.5	15.94
11/30/71	2	75	A	NO	NORM.	NORM.	6.03	0.87	3.52	0.57	9096	1268	86.0	9.85
12/1/71	3	75	A	NO	MAX.	NORM.	4.18	0.68	2.47	0.45	7256	1215	83.3	10.00
12/2/71	17	50	A	YES	NORM.	NORM.	6.35 7.05	1.15 0.85	3.85 4.28	0.79 0.60	7080	1067	84.9	10.14
12/3/71	19	50	A	NO	MAX.	NORM.	3.72	0.54	2.27	0.37	4482	659	85.3	9.56
12/6/71	21	35	A	NO	NORM.	NORM.	2.69	1.12	1.62	0.77	2412	1023	57.5	9.14
12/7/71	14	50	A	NO	NORM.	MIN.	4.82	1.16	2.76	0.76	4862	1248	74.4	10.78
12/8/71	15	50	A	NO	MIN.	NORM.	4.10	0.90	2.40	0.60	4222	956	77.5	10.44
12/9/71	22	75	D	NO	NORM.	NORM.	2.80	0.75	1.62	0.48	4286	1200	72.0	6.61

*Reduced level of soot blowing

test-to-test comparisons. The ash content of the coal determined by laboratory analysis is also provided in Table 23 as a factor affecting the measured grain loading.

As noted in Table 10, tests were performed with type A fuel at two load levels (100 MW and 50 MW) in which operating conditions were held constant except for soot blowing.

In the first of these comparisons test 7, an average value of 5.23 grains/SCF was measured at location 2. This represents an increase over the average grain loading measured in tests 11, 9, and 8 (4.38 grains/SCF). For these three tests, no soot blowing was used during the period of the test. The average ash content of the coal for tests 11, 9 and 8 was approximately equal to that measured for test 7, indicating that the differences in grain loading were not attributable to this source.

For these same tests, the grain loading measurements at location 3 were also higher for the test in which soot blowing was conducted.

At the 50 MW level, the average grain loading measured at location 2 was 6.70 grains/SCF for test 17. In this test, soot blowing was used during the test. This result is higher than any of the grain loading measurements obtained for the 50 MW A fuel tests in which soot blowing was not conducted (tests 19, 14, and 15). As was the case with the 100 MW comparisons, these 50 MW tests utilized coal of approximately the same ash content.

Two tests were run in which soot blowing was used and all other operating parameters were constant except for fuel type. In the first of these tests (test 18), B fuel was utilized. This fuel has a higher ash content than the A fuel, and for this B fuel test an average grain loading of 8.75 grains/SCF was recorded at location 2. This represents an increase over the results recorded for test 17, in which A fuel was utilized. For the A fuel test, an average grain loading of 6.70 grains/SCF was measured. These two tests indicate the degree of change in grain loading that is attributable to differences in ash content of the coal.

No specific patterns were found in the analysis of results in terms of the mechanical collection efficiencies. However, in general it was noted that greater efficiencies were noted for the tests in which B fuel was utilized.

The scope of the Baseline Measurement Test included manual measurements as well as measurements obtained by the continuous measurement systems. The manual gas measurements for NO_x, CO, CO_2, and SO_2 were determined by laboratory analysis of a grab sample. Measurements of O_2 and CO_2 were made by means of Orsat Analysis. In this section the results obtained from the continuous measurement system, and, where appropriate, a comparison is made with theoretically expected gas concentrations.

Table 11 compares continuous and manual measurement results for SO_2 with theoretical.* Table 12 gives NO_x manual as compared to NO continuous measurements. These values should be comparable since NO_2 was found to be very small. No theoretical values for NO_x were calculated since there is no convenient algorithm to calculate it. Table 13 compares O_2 and CO_2 Orsat results with continuous results. Values for CO were below detectible limits.

For those tests (Table 11) where data were available from both the manual and continuous measurements a comparison shows that at location 1 the average of the manual samples is 82 percent of the average of the theoretical values. For these same tests, the average of the continuous measurements is 95 percent of the theoretical values. The extremes of the manual measurements occur in test 5 where the manual value is 61 percent of the theoretical value, and test 13 where the manual value is 135 percent of the predicted value. The extremes for the continuous measurement at location 1 occur in test 5 where the continuous measurement is 40 percent of the theoretical value and test 13 where the continuous measurement is 119 percent of the theoretical value.

At location 3, the average of the manual measurements is 76 percent of the average of the theoretical values for the tests having both manual and continuous measurements. For these same tests, the

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*Calculated by methods from Clarke & Davidson, "Manual for Process Engineering Calculations."

TABLE 11. COMPARISON OF CONTINUOUS AND MANUAL SO_2 AT LOCATIONS 1 AND 3 WITH THEORETICAL VALUES

DATE	MITRE TEST NUMBER	TEST CONDITIONS					LOCATION 1		THEORETICAL SO_2 AT LOCATION 1	LOCATION 3		THEORETICAL* SO_2 AT LOCATION 3
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE	MANUAL	CONT.		MANUAL	CONT.	
11/8/71	11	100	A	NO	NORM.	NORM.		2055.0				
11/9/71	9	100	A	NO	MIN.	NORM.		2220.0				
11/10/71	8	100	A	NO	MAX.	NORM.	2541.3	2216.3	2075	1306		1764
11/11/71	12	100	A	YES**	NORM.	NORM.	1884.4	2281.9	2211	1703	1755.0	1879
11/12/71	7	100	A	YES	NORM.	NORM.	1571.1	2393.6	2340	1800	2042.1	1989
11/15/71	1	75	B	NO	NORM.	NORM.	1582.1	2074.1	1957	1854	1905	1663
11/16/71	6	100	B	NO	NORM.	NORM.	1272.8	1997.1	1949	1767	1897.5	1657
11/17/71	18	50	B	YES	NORM.	NORM.	1569.0	1715.0	1480	1154	1479.0	1258
11/18/71	13	35	B	NO	NORM.	NORM.	1847.5	1632.1	1366	752	1371.0	1161
11/19/71	4	75	A	NO	MIN.	NORM.	1995.8	2307.3	2551	1917	2080.0	2168
11/22/71	5	75	C	NO	NORM.	NORM.	538.8	352.5	888	443	630.0	755
11/23/71	10	100	C	YES	NORM.	NORM.	561.7	387.9	683	426	536.3	580
11/24/71	20	50	C	NO	NORM.	NORM.	546.5	471.9	627	386	566.3	533
11/30/71	2	75	A	NO	NORM.	NORM.	1812.9	1938.8	2098	1429	1740.0	1783
12/1/71	3	75	A	NO	MAX.	NORM.	1762.2	2141.3	2220	1305	1875.0	1887
12/2/71	17	50	A	YES	NORM.	NORM.	1543.9	2085.0	2480		1980.0	2108
12/3/71	19	50	A	NO	MAX.	NORM.	1732.6	1897.5	2070	861	1815.0	1759
12/4/71	21	35	A	NO	NORM.	NORM.	1415.2	1875.0	2221	451	1680.0	1888
12/7/71	14	50	A	NO	NORM.	MIN.		1743.8			1782.9	
12/8/71	15	50	A	NO	MIN.	NORM.		2107.5				
12/9/71	22	75	D	NO	NORM.	NORM.		735.0			2062.5	

*15 percent leakage assumed between 1 and 3

**reduced level of soot blowing

TABLE 12. COMPARISON OF CONTINUOUS AND MANUAL NO_x AT LOCATION 3

DATE	MITRE TEST NO. (OLD)	TEST CONDITIONS							MANUAL NO_x LOCATION 2	MANUAL NO_x LOCATION 3	CONTINUOUS NO MEASUREMENTS LOCATION 3
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	MEASURED EXCESS AIR LOCATION 2	MEASURED EXCESS AIR LOCATION 3	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	81.5	64.2	NORM.	397	651	
11/9/71	9	100	A	NO	MIN.	64.2	36.6	NORM.	304	378	
11/9/71	9	100	A	NO	MIN.	64.2	36.6	NORM.	390	411	
11/10/71	8	100	A	NO	MAX.	59.6	47.3	NORM.	433	453	
11/10/71	8	100	A	NO	MAX.	59.6	47.3	NORM.		591	
11/11/71	12	100	A	YES*	NORM.	43.2	60.5	NORM.	513	349	
11/11/71	12	100	A	YES*	NORM.	43.2	60.5	NORM.	505	436	
11/12/71	7	100	A	YES	NORM.	38.6	38.3	NORM.	287	321	
11/12/71	7	100	A	YES	NORM.	38.6	38.3	NORM.	363	437	
11/16/71	6	100	B	NO	NORM.	42.7	40.3	NORM.	447	466	
11/16/71	6	100	B	NO	NORM.	42.7	40.3	NORM.	481	466	285
11/15/71	1	75	B	NO	NORM.	61.9	57.4	NORM.	464	419	350
11/15/71	1	75	B	NO	NORM.	61.9	57.4	NORM.	463	461	395
11/17/71	18	50	B	YES	NORM.	72.5	58.5	NORM.	246	570	
11/17/71	18	50	B	YES	NORM.	72.5	58.5	NORM.	485	684	365
11/18/71	13	35	A	NO	NORM.	87.8	69.3	NORM.	464	387	
11/18/71	13	35	B	NO	NORM.	87.8	69.3	NORM.	587	443	335
11/19/71	4	75	A	NO	MIN.	30.7	27.4	NORM.	319	330	375
11/19/71	4	75	A	NO	MIN.	30.7	27.4	NORM.	385	271	333
11/22/71	5	75	C	NO	NORM.	35.4	42.5	NORM.	339	308	240
11/22/71	5	75	C	NO	NORM.	35.4	42.5	NORM.	328		
11/23/71	10	100	C	YES	NORM.	52.7	41.3	NORM.	223	367	100
11/23/71	10	100	C	YES	NORM.	52.7	41.3	NORM.	243	264	105
11/24/71	20	50	C	NO	NORM.	30.3	34.4	NORM.	279	235	150
11/24/71	20	50	C	NO	NORM.	30.3	34.4	NORM.	267	262	145
11/30/71	2	75	A	NO	NORM.	35.0	36.8	NORM.	467	412	345
11/30/71	2	75	A	NO	NORM.	35.0	36.8	NORM.	552	450	335
12/1/71	3	75	A	NO	MAX.	47.1	52.5	NORM.	294	426	
12/1/71	3	75	A	NO	MAX.	47.1	52.5	NORM.	410	558	340
12/2/71	17	50	A	YES	NORM.	38.5	38.3	NORM.	341	323	
12/2/71	17	50	A	YES	NORM.	38.5	38.3	NORM.	347	295	345
12/3/71	19	50	A	NO	MAX.	64.3	69.3	NORM.	436	406	
12/3/71	19	50	A	NO	MAX.	64.3	69.3	NORM.	358	403	
12/4/71	21	35	A	NO	NORM.	51.7	61.2	NORM.	344	368	
12/4/71	21	35	A	NO	NORM.	51.7	61.2	NORM.	389	276	195

* REDUCED LEVEL OF SOOT BLOWING

TABLE 13. COMPARISON OF CONTINUOUS O_2 AND CO_2 WITH ORSAT MEASUREMENTS AT LOCATION 3

DATE	MITRE TEST NUMBER	TEST CONDITIONS					O_2		CO_2	
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE	CONT.	ORSAT	CONT.	ORSAT
11/8/71	11	100	A	NO	NORM.	NORM.	----	.084	----	.108
11/9/71	9	100	A	NO	MIN.	NORM.	----	.058	----	.128
11/10/71	8	100	A	NO	MAX.	NORM.	----	.070	----	.110
11/11/71	12	100	A	YES*	NORM.	NORM.	----	.080	----	.1225
11/12/71	7	100	A	YES	NORM.	NORM.	.0625	.060	.135	.125
11/15/71	1	75	B	NO	NORM.	NORM.	.071	.078	.141	.118
11/16/71	6	100	B	NO	NORM.	NORM.	.0675	.062	.138	.126
11/17/71	18	50	B	YES	NORM.	NORM.	.075	.079	.1355	.116
11/18/71	13	35	B	NO	NORM.	NORM.	.0852	.088	.128	.104
11/19/71	4	75	A	NO	MIN.	NORM.	.062	.047	.142	.131
11/22/71	5	75	C	NO	NORM.	NORM.	.032	.065	.124	.103
11/23/71	10	100	C	NO	NORM.	NORM.	.060	.065	.1311	.099
11/24/71	20	50	C	NO	NORM.	NORM.	.0706	.057	.1264	.106
11/30/71	2	75	A	NO	NORM.	NORM.	.0615	.058	.140	.131
12/1/71	3	75	A	NO	MAX.	NORM.	.0807	.074	.132	.118
12/2/71	17	50	A	YES	NORM.	NORM.	.074	.066	.1348	.126
12/3/71	19	50	A	NO	MAX.	NORM.	.086	.088	.126	.104
12/4/71	21	35	A	NO	NORM.	NORM.	.0776	.082	.125	.106
12/7/71	14	50	A	NO	NORM.	MIN.	.0705	.061	.1411	.126
12/8/71	15	50	A	NO	MIN.	NORM.	.0695	.067	.138	.122
12/9/71	22	75	D	NO	NORM.	NORM.	.0565	.063	.1362	.126

* REDUCED LEVEL OF SOOT BLOWING

average of the continuous measurement is 100 percent of the average of the theoretical values. The extremes for the manual measurements occur in test 21 where the manual value is 24 percent of the theoretical value and test 1 where the manual value is 111 percent of the theoretical value. The extremes for the continuous measurement occur in test 21 where the continuous measurement is 89 percent of the theoretical value and test 1 where the continuous measurement is 114 percent of the theoretical value.

Table 12 provides a comparison of the continuous and manual measurements for NO_x at location 3. Manual measurements taken at location 2 are also provided in this table. No consistent patterns are noted in Table 12 with respect to the effect of test conditions on NO_x concentrations, with the exception of fuel type. For the test performed with C fuel (gas and coal mixed) the NO_x levels were significantly lower than for the tests performed with A and B fuel.

A comparison of continuous O_2 and CO_2 measurements and Orsat measurements is provided in Table 13. A comparison of the average of the continuous O_2 and the Orsat O_2 measurements shows good agreement whereas the average of the continuous CO_2 measurements were higher than the average of the Orsat CO_2 measurements.

Ultimate and proximate analyses of coal were performed on each of the 21 tests on an as received and daily basis. Proximate analyses were also performed on fly ash removed from the dust collector and air heater and ash samples from the furnace bottom and pulverizer reject. The results of these analyses are presented in Appendix D.

Trace element concentrations were determined on four of the tests in the Baseline Program in the coal pulverizer rejects from the coal mills, bottom ash (slag), and the fly ash collected in the air heater, the mechanical collector, and locations 2 and 3.

The trace element concentrations were also determined for samples of fly ash collected from location 2 and location 3 for four tests in the program. The results of the trace elemental analyses are summarized in Appendix D along with the proximate and ultimate analyses.

Additional trace elemental analyses were provided by EPA on pulverized coal for six of the test runs are also listed in Appendix D.

Bound constituents were determined by chemical analysis for fly ash samples collected at location 2 and location 3. The results of these analyses are provided in Tables 14 and 15.

As noted in Table 14, the bound SO_2 concentration (measured as sulfates) range from 0.15 microgram to 0.88 microgram per milligram of particulate matter. For the two tests representing these extremes (test 22 and test 8), the measured particle emission rates at location 3 were, respectively, 1200 lbs/hour and 2166 lbs/hour. The measured gaseous SO_2 mass flow rates at location 3 for these tests were 1452 lbs/hour and 3810 lbs/hour, respectively. Multiplying the bound SO_2 concentration ranges by the particle emission rates provides a

TABLE 14. DETERMINATION OF BOUND SO_2 AND SO_3 BY CHEMICAL ANALYSIS

TEST NO.	LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE	SO_2 MICROGRAM/ MILLIGRAM PARTICULATE	SO_3 MICROGRAM/ MILLIGRAM PARTICULATE	LOCATION
8	100	A	NONE	MAX.	NORM.	0.77	5.77	2
8	100	A	NONE	MAX.	NORM.	0.88	7.65	3
1	75	B	NONE	NORM.	NORM.	0.30	9.34	2
1	75	B	NONE	NORM.	NORM.	0.39	24.10	3
5	75	C	NONE	NORM.	NORM.	0.16	0.67	2
5	75	C	NONE	NORM.	NORM.	0.16	15.84	3
17	50	A	MAX.	NORM.	NORM.	0.37	13.69	2
17	50	A	MAX.	NORM.	NORM.	0.35	3.77	3
22	75	D	NONE	NORM.	NORM.	0.4	2.25	2
22	75	D	NONE	NORM.	NORM.	0.15	1.63	3

TABLE 15. DETERMINATION OF POLYNUCLEAR AROMATIC COMPOUNDS BOUND TO THE SURFACE OF FLUE GAS PARTICULATES

DATE:	11/10/71	11/15/71	11/22/71	12/2/71	12/9/71
MITRE TEST NO.:	8	1	5	17*	22
TEST CONDITIONS					
Load Factor:	100	75	75	50	75
Fuel Type:	A	B	C	A	D
Soot Blower:	None	None	None	Maximum	None
Excess Air:	Maximum	Normal	Normal	Normal	Normal
Burner Angle:	Normal	Normal	Normal	Normal	
TOTAL					
RECOVERY %					
Location 2	100.0	No Peaks	91.7	25.0	37.5
Location 3	100.0	17.7	100.0	31.2	No peaks
BENZO(α)PYRENE (μg)					
Location 2			21.80	200.00	74.67
Location 3		259.89	126.00	185.90	
CONCENTRATION (μg/mg)					
Location 2			0.17	0.72	1.16
Location 3		3.00	0.87	0.83	
OTHER POSSIBLE COMPONENTS					
Location 2	Anthanthrene				
Location 3	Anthanthrene			Chrysene; 1,2-Benzanthrecene	

* Two samples were collected at each location during this test. Both samples were combined for the determination of surface adsorbed polynuclear aromatic compounds.

mass emission rate of bound SO_2 in terms of lbs/hour. Comparison of the mass rate against the gaseous mass flow rates shows that the amount of bound SO_2 released to the atmosphere is on the order of 10^{-10} of the mass released in gaseous form.

Measurement of gaseous SO_3 mass flow rates was not successfully accomplished in the baseline test due to problems with sample handling. For this reason, no comparison can be made between the adsorbed SO_3 (measured as sulfites) and the gaseous SO_3.

Table 15 is self-explanatory and provides the polynuclear aromatic hydrocarbons bound to the surface of the particulates matter. Highest confidence should be placed on those tests with the highest percent of recovery (i.e., the percentage of the original mass which can be accounted for as extracted organic material and particulate fly ash). As noted in Table 15, the organic materials found were Benzo(α)Pyrene, and possibly Anthanthrene, Chrysene, and 1,2-Benzanthrecene.

The chemical state of the sulfur adsorbed on the surface of fly ash samples was also determined by the Oak Ridge National Laboratory. The results of these analyses appear in detail in M73-42, "Baseline Measurement Test Results for Cat-Ox Demonstration Program." Three techniques were used by the Oak Ridge National Laboratory to examine each of ten fly ash samples: photoelectron spectroscopy (ESCA), surface area determination by the BET method, total sulfur determination by combustion analysis. One of the specimens was also examined by infrared spectroscopy.

The following are firm conclusions that can be made:

1. The photoelectron spectroscopy results show that the oxidation state of sulfur on the surfaces of all ten samples is +6.

2. The high intensities of photoelectron peaks arising from sulfur indicate that in all samples most of the sulfur is segregated at the surface rather than distributed homogeneously in the solid phase.

3. Surface area measurements and total sulfur determinations show that the degree of surface coverage by sulfate salts varies 5-40 monolayers.

4. The spectrum of the sample studied by infrared spectroscopy shows that sulfur is present on the surface as sulfate rather than as adsorbed SO_3. Apparent discrepancies between this conclusion and the findings of MRI can be explained by the greater sensitivity of the wet chemical methods used by MRI as compared with infrared spectroscopy.

The following observations were also made; however, it was felt that more study would be needed before they could be stated as firm conclusions:

1. Binding energies of S_2 p electrons, determined by photoelectron spectroscopy, closely match those for sulfates of polyvalent cations such as Fe^{+2}, Fe^{+3}, and Ca^{+2}. The sulfur may be present on the fly ash surfaces as calcium or iron sulfate.

2. Photoelectron peaks for silicon were broadened. This suggests the presence of more than one chemical state of silicon. The +4 oxidation state, indicating silicates of SiO_2, is definitely present, but lower oxidation states may be present also. Different glass phases containing silicon may also have caused the peak broadening. More study is necessary to be sure that the broadening of the silicon peaks is not due to interference by other elements.

Conclusions--All primary objectives of the Baseline Measurement Test were achieved in the five-week period of testing on Steam Generator Unit No. 4 of the Wood River Station of the Illinois Power Company.

A relationship was defined between control settings and operating conditions for Unit No. 4 and flue gas properties at the Cat-Ox/ Steam Generator interface; baseline performance of the steam generator was characterized in terms of emission levels and quantitative data were obtained which can be used to support the establishment of realistic performance standards. Operating experience was also obtained in the testing and calibration of the measurement procedures and hardware to be used in the one-year demonstration test, and quantitative information was obtained on the overall operability and reliability of Steam Generator Unit No. 4.

Data are provided in this report in the form of tabular results for a set of twenty-one separate tests, each at different operating conditions. To maintain those conditions during each test (a period of approximately ten hours), it was necessary to control load factor, fuel type, soot blowing, and excess air.

In general, no test results were found that were significantly different from anticipated results, either in terms of magnitude or in terms of effects of the parameters examined.

Net and gross efficiencies were, on the average, higher at a 75 MW load level when compared with average values at 100 MW and 50 MW load levels, but the differences were not of a magnitude to be significant. No significant differences were found in net and gross efficiencies for the three types of fuel tested at the 100 MW level.

Measured gas mass flow rates for sulfur dioxide were consistent with control settings and sulfur content of the fuel. Measured gas flow rates for carbon dioxide were not significantly different for the three types of fuel tested. Oxygen mass flow rates decreased with decreased load level, and were found not to be significantly different for the two fuel types for a fixed load level. Measured gas mass flow rates for nitric oxide were significantly lower for tests performed with the fuel type that was predominantly natural gas than for tests performed with the other two fuel types.

Total gas mass flow rates were derived from the measured flow rates for individual gases (i.e., same decrease with decreasing load level and same increase with increased excess air).

The results of a sulfur balance computation, comparing measurements of sulfur flow input to the system in the fuel with sulfur flow output for the system in the stack gas, were in good agreement for all tests. The results led to the conclusion that the total combined error in sulfur dioxide and gas flow measurements was low.

Grain loading measurements were found to be consistent with the ash content of the fuels utilized and the soot blowing cycle employed. No specific patterns were found in the analysis of results in terms of mechanical collection efficiencies.

In the comparisons between manual sampling and continuous measurement results with theoretical expected values of gaseous concentrations, closer agreement was found between the continuous measurement results and the theoretical values.

The proximate and ultimate anlayses of the coal and the elemental analysis of pulverizer rejects, furnace bottom ash, and fly ash did not provide any specific pattern beyond the expected results. The elemental analyses are of special value, however, in that they do provide the means for determining emission rates to the ambient atmosphere for a number of elements not usually examined in emission testing programs.

Acceptance Test

The only information gathered on the totally operational Cat-Ox system was collected during the Monsanto/IPC Performance Guarantee Test. All the data presented and analyzed in this section are taken from the Monsanto report of those tests.* Discussions relating to Cat-Ox system acceptance and history are covered in Section 1 of this document. Only the test results and their implications toward the systems operation are discussed here. Figure 10 shows the test plan for sample and information retrieval based on an uninterrupted 24-hour test.

Test Objectives--The prime objective of this test series was to demonstrate that Cat-Ox could fulfill the requirements of the Process Performance Guarantee agreed upon between Monsanto and IPC on July 9, 1970.

The operating requirements are listed in Table 16. Monsanto guaranteed the fulfillment of the conditions specified in Table 16 if the Enviro-Chem Engineering design and operating instructions were followed. The fuel type burned in Unit 4 was to be the same as specified by IPC on April 2, 1970. The flue gas was to contain no more than 0.26 percent SO_2 and no less than 3.3 percent O_2. The converter would be loaded with the specified amount of Cat-Ox A Catalyst and have an input temperature maintained between 830°F and

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*"Performance Guarantee Test, Cat-Ox System - Unit 4 Wood River Station IPC," July 1973, B.G. Ward, Monsanto Enviro-Chem Systems, Inc.

ELAPSED TEST TIME (HOURS)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Unit 4 Data	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Cat-Ox Data	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Coal Sample			X				X				X				X				X				X		
Acid Sample			X				X				X				X				X				X		
Stack Mist Loading			←	---	---	---	---	---	→		←	---	---	---	---	---	→	←	---	---	---	---	---	---	→
SO_2 Ppt. Inlet	cX	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX	X
SO_2 Converter Inlet	cX	X	X	X	cX	X	X	X	X	X	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX
SO_2 Converter Outlet	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX	X	X	X	cX
SO_2 Stack Inlet	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Dust Loading Ppt. Inlet				←	---	---	---	→				←	---	---	---	→			←	---	---	---	---	→	
Dust Loading Stack			←	---	---	---	---	---	→		←	---	---	---	---	---	→	←	---	---	---	---	---	---	→
Gas Composition Ppt. Inlet	←	→							←	→							←	→						←	→
Gas Composition Stack	←	→							←	→							←	→						←	→
Pitot Traverse Ppt. Inlet	←	→							←	→							←	→						←	→
Pitot Traverse Stack	←	→							←	→							←	→						←	→

X - Data Point
c - Instrument Calibration

FIGURE 10. CAT-OX PLANNED ACCEPTANCE TEST

TABLE 16. OPERATING PARAMETERS GUARANTEED

Maximum Capacity Input Flue Gas	1,120 x 10^3 lb/m @ 310°F 1.5" H_2O
Acid Strength	$\geq$ 60° Baume (77.7% H_2SO_4)
Mist Emitted	<1.0 mg 100% H_2SO_4/ACF @ capacity
$SO_2 \rightarrow SO_3$ Conversion	90% or greater
Fly Ash Removed	99% @ rated capacity
SO_2 Removed	85%

900°F. Further, it was required that all equipment interfaced with Cat-Ox be in good operating condition.

Schedule and Results--The performance guarantee test began at 1700 hours 26 July 1973 after some initial analyzer problems. The load was set at 98 MW since tests on 25 July 1973 indicated mass flow at Unit 4 boiler capacity (102 MW) was in excess of design by about 8 percent. Nine and one-half hours into the test the by-pass damper tripped open from excess pressure at the output of the ESP and at the Mist Eliminator (0235, 27 July 1973).

Preliminary flow calculations shows that at 98 MW the boiler mass flow exceeded Cat-Ox capacity by 9 percent ($1.22\text{-}1.23 \times 10^6$ lbs/hr). As a result, the unit load was lowered to 92 MW.

Testing continued until 1130 hours 27 July 1976 when an I.D. fan outage occurred. Everything indicated that Cat-Ox was under control at the time of the outage. The system was started again at 1330 hours with no explanation for the outage available.

Since neither outage described above could be shown due to Cat-Ox malfunction, at 2130 hours 27 July 1973 Cat-Ox had officially completed the 24-hour Guarantee Test period. Cat-Ox continued to operate after that point and the following outages occurred:

1. 2300 hours 27 July 1973 (25-1/2 hours) 5 hours out due to failure of "B" burner during an electrical storm
2. 0815 hours 28 July 1973 (29-3/4 hours) 30 minute coal flow fluctuations caused "B" burner out

3. 1600 hours 28 July 1973 (32 hours) load was lowered to 72 MW to further prove extended reliability.

The testing of the burners on fuel oil at 72 MW continued to 0900 hours 27 July 1973.

It was mutually agreed by Enviro-Chem personnel and Illinois Power personnel that the test period between 1700 hours 26 July 1973 and 2300 hours 27 July 1973 constituted an "acceptable 24 substantially consecutive hour performance test period." The data outside this test period were also deemed acceptable since an excessive flow rate was experienced early in the test period.

Gas Flow Measurement--Volume flow was measured at two locations: at the input to the ESP and at the mid-point of the stack. All measurements were made in accordance with the 1971 (December 23) Federal Register.

The Cat-Ox system design capacity is 1,120,000 lbs/hr at 310°F, 1.5 in H_2O. Initial tests on 25 July 1973 before the start of the 24-hour test resulted in flow rates of 1.22-1.23 X 10^6 lb/hr at 102 MW. For this reason, the tests were run at 98 MW initially. However, measurements on 16 July 1973 indicated mass flow at this load was also above rated capacity (Table 17 lists the volume flow data gathered during the test period). The load was subsequently lowered to 92 MW which produced a flow nearer the rated capacity. The O_2 readings at the economizer were below 4 percent. At one duct

TABLE 17. CAT-OX GAS VELOCITY DATA

Date	Actual Time Hours	Location	Gas Flow ACFM	Gas Temp. °F	Molecular Weight	Gas Flow lb./hour
7/26/73	1200-1300	Ppt. inlet	401,559	326	29.19	1,213,000
		Stack	440,575	239	29.10	1,491,000
7/26/73	2300-2400	Ppt. inlet	392,916	303	29.47	1,234,000
		Stack	356,455	239	29.47	1,222,000
7/27/73	1400-1500	Ppt. inlet	381,936	340	29.07	1,128,000
		Stack	368,562	240	29.14	1,247,000
7/28/73	0930-1030	Ppt. inlet	389,471	333	29.44	1,176,000
		Stack	377,546	240	28.95	1,266,000

the ESP inlet the O_2 measurement was 6-7 percent while at the other duct, it remained below 4 percent.

It was noted that the flow over one side of the ESP (the side with 6-7 percent O_2) was lower than the other side. The effects of this variable input flow on the ESP is discussed in the special tests section.

Fly Ash Removal--Particle loading measurements were performed at the stack and input of the ESP using the ASME method. At the stack, standard alundum thimbles were replaced by 47 mm Gelman Fiberglass units. Sample handling procedures outlined in Federal Register 23 December 1971 were followed.

Table 18 lists the results of the mass loading tests. Tests 4-3 and 4-4 included a loading of 0.008 and 0.007 gr/SCF, respectively (efficiency of 99.5 percent). Mass loading results from tests 4-1 and 4-2 were much higher. The filters were contaminated with a green crystalline material which was not apparent on the filters in any of the other tests. Test 4-1 and 4-2 were performed when the unit was operating above the rated capacity. Hence, these filters were considered contaminated and results erroneous. The fly ash removal values presented in Table 18 are for the Cat-Ox system only. When the fly ash removal of the mechanical collector is combined with these results, the additive removal exceeds the required value.

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*The system is described in "Atmospheric Emissions from Sulfuric Acid Manufacturing Processes," U.S. Department of Health, Education and Welfare. 979-AP-13, 1965.

TABLE 18. PARTICLE LOADING FOR ACCEPTANCE TESTS

Test No.	Date	Actual Time Hours	ESP Inlet		Stack		% Removal (gr/SCF basis)
			gr/ACF	gr/SCF	gr/ACF	gr/SCF	
4-1	7/26/73	1240-2200	0.983	1.730	0.031	0.049	97.2
4-2	7/27/73	0040-0230 0500-0820	0.823	1.382	0.049	0.076	94.5
4-3	7/27/73	1400-1900	0.958	1.736	0.005	0.008	99.5
4-4	7/27/73	2300-		Aborted during electrical storm.			
4-5	7/28/73	1100-1440	0.866	1.523	0.004	0.007	99.5

Acid Mist--Sampling for acid mist was performed at the stack with a Brink BMS-10 Mist Sampler System. The tests were run simultaneously with particle sampling and the results are presented in Table 19. It is apparent from the table that the loading never exceed the 1.0 milligram 100 percent H_2SO_4/ACF during these tests. Sampling performed during mist eliminator washing indicated no increase in H_2SO_4 mist during that phase of the operation.

SO_2 Conversion and Removal Table 20 is a summary of the SO_2 data gathered during the test. Since all locations could not be recorded simultaneously, the SO_2 data were integrated over a sampling period and conversion efficiencies were calculated from these results. As can be seen from the table, the conversion and removal efficiency was greater than 90 percent, hence, meeting the performance guarantee requirements.

A discrepancy in SO_2 values at the converter inlet and ESP inlet is apparent, the former being 89 percent of the latter. Though gas dilution from the burners could account for some of the disagreement, the majority is probably due to the sampling at the converter. This location has gas flows that are extremely turbulent and segregated.

Figures 11 to 13 show a SO_2 profile across the various locations.

Coal Analysis--Coal samples were taken from the four coal mills and integrated for analysis. The results are presented in Table 21. There were no unusual or surprising results produced from this analysis.

Cat-Ox Acid Strength--Table 22 presents the results of acid strength test performed on segregated samples taken from the product

TABLE 19. SULFURIC ACID MIST EMITTED TO THE STACK

Date	Actual Time (Hours)	Mist Loading mg 100% H_2SO_4/ACF
7/26/73	1220-2130	0.529
7/27/73	0030-0230 0500-0900	0.433
7/27/73	1105-1130 1540-1915	0.251
7/28/73	0535-0755	0.440
7/28/73	1100-1352	0.275

TABLE 20. MEAN SO_2 LOADINGS ACROSS CAT-OX

Location	24 Hour Test Data ppm SO_2/hours of monitoring	Accumulated Data ppm SO_2/hours of monitoring
ESP Inlet	2203/23.2	2183/38.7
Converter Inlet	1947/16.7	1958.5/28
Converter Outlet	133/22.7	139/34.7
Stack Inlet	173.5/16.7	188/27.7
% SO_2 Conversion	93.2	92.9
% SO_2 Removal	92.1	91.4

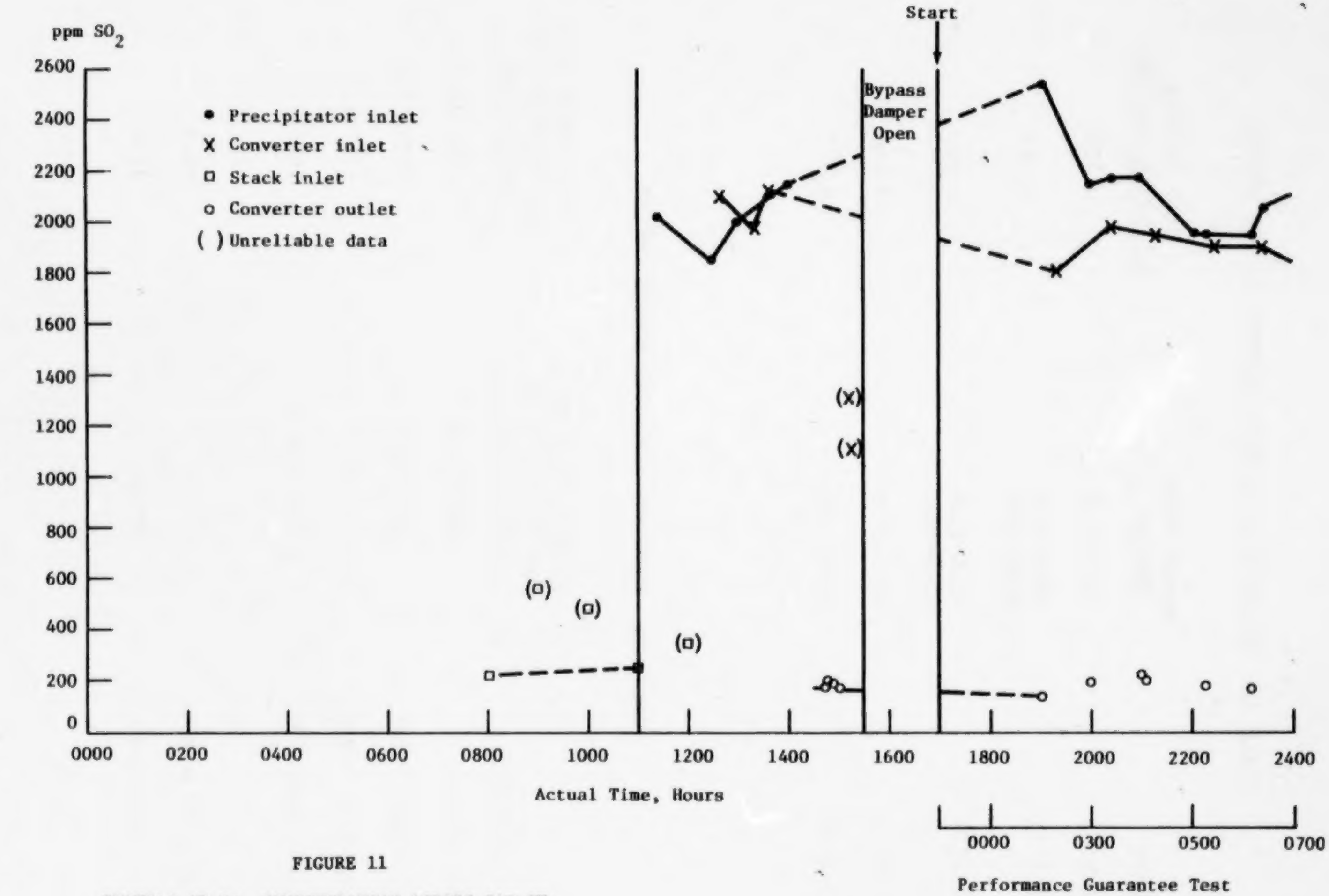

FIGURE 11

PROFILE OF SO_2 CONCENTRATION ACROSS CAT-OX
7/26/73

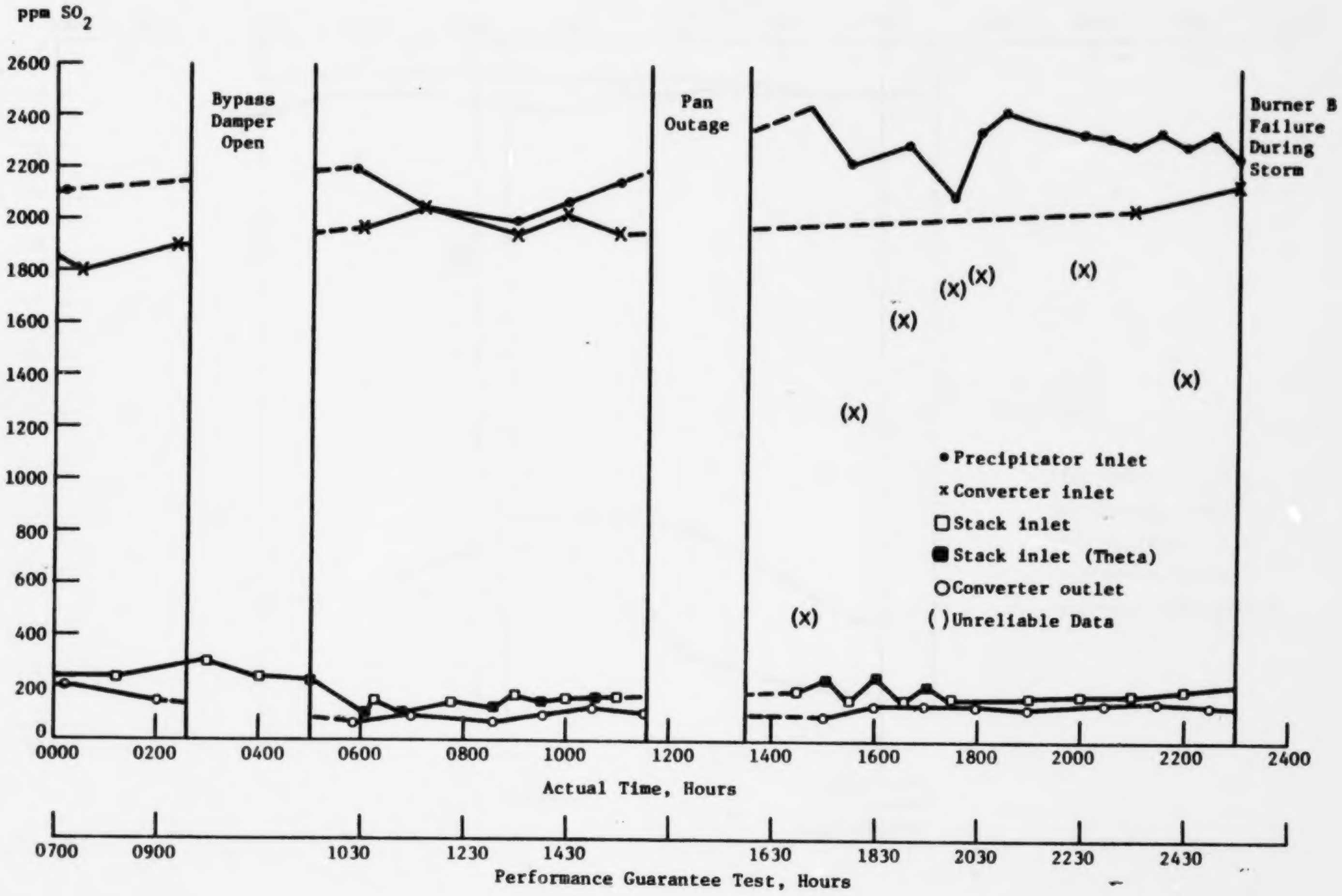

FIGURE 12

PROFILE OF SO_2 CONCENTRATION ACROSS CAT-OX
7/27/73

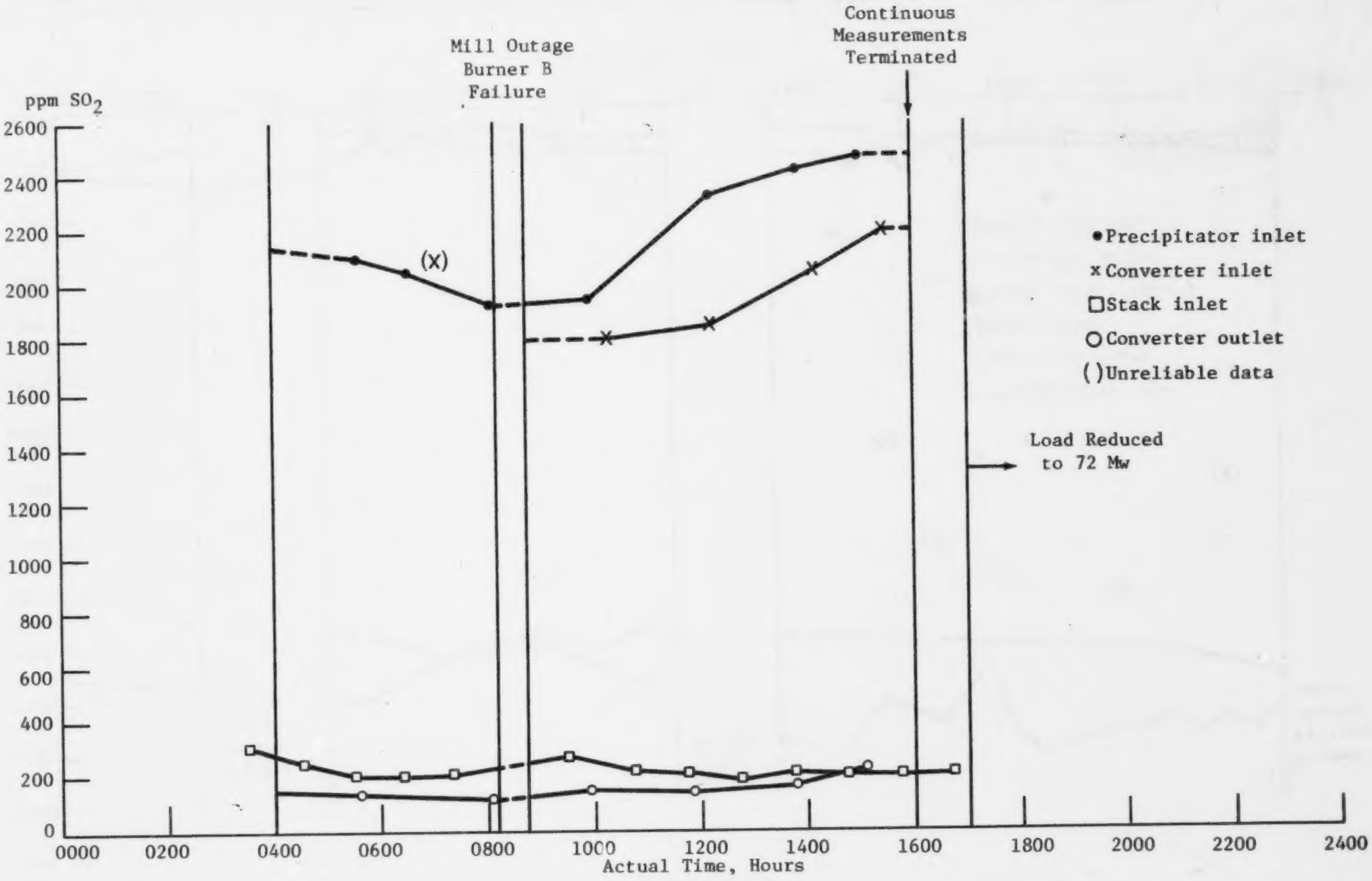

FIGURE 13

PROFILE OF SO_2 CONCENTRATION ACROSS CAT-OX
7/28/73

TABLE 21. COAL SAMPLE ANALYSES

Composition % by weight as received	7/26/73		7/27/73		Composite	Fuel Specification 4/2/70
	1900 hours	2300 hours	0800 hours	1500 hours		
C	65.74	65.89	66.53	66.31	66.17	61.43
H	4.34	4.33	4.51	4.52	4.44	4.38
S	3.42	3.41	3.40	3.43	3.42	3.11
N	1.09	1.09	1.09	1.08	1.09	----
O	10.26	10.16	9.87	9.59	10.22	9.46
Ash	11.54	11.44	10.60	11.30	11.12	10.12
H_2O	3.61	3.67	4.00	3.09	3.54	11.50
Heating Value Btu/lb	11,900	11,930	12,100	12,080	12,020	11,070

TABLE 22. CAT-OX SULFURIC ACID STRENGTH

Date	Actual Time (Hours)	Acid Strength (% H_2SO_4)
7/26/73	1800	86.4
7/26/73	2300	85.9
7/27/73	0400	83.5
7/27/73	0800	81.5
7/27/73	1100	78.9
7/27/73	1900	80.6
7/27/73	2400	80.6
7/28/73	0600	79.3
7/29/73	0200	76.0
7/29/73	0600	76.2
Segregated acid 7/26/73 - 7/29/73		78.7

Acid concentrations were established by concentration density determinations. The initially high acid strength was caused by high acid temperature at the exit of the absorbing tower (330°F) and higher gas flows. More typical conditions were experienced as acid temperature decreased (0800 27 July 1973).

Conclusions--Illinois Power Co. and Monsanto Enviro-Chem personnel agreed that between 1700 hrs 23 July 1973 and 2300 hours 27 July 1973 Cat-Ox fulfilled the performance guarantee.

The data demonstrated that Cat-Ox could produce an acceptable strength acid while removing sufficient amounts of SO_2 from the flue gas. The H_2SO_4 mist in the exit gas was continually below the 1 mg (100 percent H_2SO_4)/ACF specified. The particle measurements also met the specified standards with the exception of tests 4-1 and 4-2 which were contaminated. The problems experienced with those filters were probably due to sampling at lower than acceptable temperatures and were erroneous. These tests also indicate the first observations of non-uniform flow over the ESP. The effect of non-uniform flow on the ESP will be negative and is discussed later in Section V. However, what is pertinent here is that had the flow been uniform the ESP efficiency would have most likely increased.

Two problems hindered Cat-Ox operation:

1) Problems with the initial burners
2) Overloading of the Brinks mist eliminator with ash from the oil burners

Both problems were the result of the poor internal burner reliability.

The tests also emphasized that the Unit 4 boiler would have to be operated slightly below its maximum capacity or with some gas by-pass so as not to exceed Cat-Ox capacity.

In general, these tests indicated that Cat-Ox would indeed operate at its design capacity and specifications if the problems with the reheat burners could be corrected.

ESP TESTS

Test Objective

The primary objective of this test program was to evaluate the ESP as a control device with regard to ESP performance characteristics not extensively measured in the past. The precipitator is integrated with the flue gas output of the 100 MW unit 4 steam generator. The ESP was designed to remove 99.6 percent of the particulate matter entering it or maintain an output of 0.005 gr/SCF or less. These were the requirements necessary to satisfy the inlet conditions to the Cat-Ox SO_2 control process.

The specific areas of ESP investigation include the efficiency of particle collection as a function of particle size from 0.01 μm to 5 μm and the comparison of the effects of various parameter variations between measured results and computer-predicted results. The computer simulation model was developed by SRI under a separate EPA contract.

Schedule

The actual test schedule and ESP control settings are shown in Table 23. A total of 15 tests were performed. The original test sequence was modified to obtain additional time for a reliable particle count in the diffusional particle size at the inlet of the ESP and because unit No. 4 generator developed difficulties during the test program.

TABLE 23. ELECTROSTATIC PRECIPITATOR TEST PROGRAM

TEST NO.	RUN NO.	DATE (1973)	WEEK	STEAM GENERATOR OPERATING CONDITIONS			ESP OPERATING CONDITIONS*		TEST OBJECTIVES
				LOAD	COAL	SOOT BLOWING	PLATE CURRENT	TRANSFORMER SETS	
1	1 2 3	Sept. 11 (Night)	1st	103 85 70	High Sulfur	None	Automatic (55 $\mu A/ft^2$)	Normal	Calibration of gas volume flow
		12							MRI checkout equipment; SRI install voltage dividers
2	1 2	13 (Day)		103	High Sulfur	Retractables Wall	Automatic	Normal	ESP performance with soot blowing
3	1 2	14 (Day)		103	High Sulfur	None	Automatic	4th Sect. Off	ESP performance with last section off
15	1	15 (Day)		103	High Sulfur	None	---	---	Characterization of EPS inlet for diffusional Particle size range (0.01-0.15 µm)
		16-19	2nd						Steam generator under repair
8	1	19 (Day)		103	High Sulfur	None	---	---	Characterization of ESP inlet for diffusional Particle Size Range (0.01-0.15 µm)
4	1 2	19 (Day)		103	High Sulfur	None	Automatic	Normal	ESP performance under normal operation
5	1 2	20 (Day)		103	High Sulfur	None	20 $\mu A/ft^2$	Normal	ESP performance at lower current density
6	1 2	21 (Day)		103	High Sulfur	None	10 $\mu A/ft^2$	Normal	ESP performance at lower current density
7	1 2	22 (Day)		103	High Sulfur	None	30 $\mu A/ft^2$	Normal	ESP performance at lower current density
9	1 2	24-25 (Night)	3rd	85	High Sulfur	None	Automatic	Normal	ESP performance at intermediate load
10	1 2	25-26 (Night)		70	High Sulfur	None	Automatic	Normal	ESP performance at low load
11	1 2	26-27 (Night)		70	High Sulfur	None	30 $\mu A/ft^2$	Normal	ESP performance at low load and current density
12	1 2	27-28 (Night)		70	High Sulfur	None	20 $\mu A/ft^2$	Normal	ESP performance at low load and current density
13	1 2	28-29 (Night)		70	High Sulfur	None	10 $\mu A/ft^2$	Normal	ESP performance at low load and current density
		29							Conversion to low-sulfur coal
14	1 2	Oct. 1 (Day)	4th	103	Low Sulfur	None	Automatic	Normal	ESP performance with low-sulfur coal

*Collecting plate rapping conditions and discharge wipe vibration conditions constant throughout test program.

As can be seen from Table 23 for each variation of Plate current i.e., $30\ \mu A/ft^2$, $20\ \mu A/ft^2$, $10\ \mu A/ft^2$, or automatic operation, a series of tests was run. For each test for a given set of conditions (coal, soot blowing, plate currents or transformer sets), the steam generator was operated at 103 MW, 85 MW, or 70 MW. A number of tests were repeated as shown in Table 23. The steam generator was brought to each specific load about 4 hours prior to the test. In some cases (during low load tests) the 4 hour pre-soak could not be satisfied because demands on IP required them to maintain a higher load during the pre-soak period.

Table 24 shows the parameters measured for each test. Table 25 shows the method employed for each test as well as locations where samples or data were taken.

Three different methods of particle sizing were used to cover the entire 5 μm to 0.01 μm range. Sampling was anisokinetic since the particle size range of interest does not require isokentic sampling.

Along with the on site analysis, ash, fly ash and coal samples were sent out for chemical analysis. These data along with the other data were used to characterized the flue gas entering the ESP and leaving the ESP such that any variation or fluctuation in the compositions or character of the steam generation effluents which might result in a change in ESP efficiency would be recorded. A more comprehensive explanation of measurement methods and parameters is

TABLE 24. PARAMETERS MEASURED DURING TEST PROGRAM

TEST NO.	RUN NO.	DATE (1973)	WEEK	MITRE										SRI				MRI			
				GAS CONCENTRATION				GAS VOL. FLOW			MANUAL			MANUAL				MANUAL			
				SO_2	CO_2	O_2	H_2O	ΔP	SP	T	GB	CS	SV	SV	IR	CN	CL	ML	I	SO_3	AS
1	1	Sept. 11	1st		X	X	X	X	X	X	X										
	2	(Night)			X	X	X	X	X	X	X										
	3				X	X	X	X	X	X	X										
		12																			
2	1	13		X	X	X	X	X	X	X	X	X	X					X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
3	1	14		X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
15	1	15		X	X	X	X	X	X	X	X					X (Inlet)	X				
		(Day)																			
		16-19	2nd																		
8	1	19 (Day)		X	X	X	X	X	X	X	X					X (Inlet)	X				
4	1	19		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X		X	X	(Outlet)		X	X	X	X
5	1	20		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X		X	X	(Outlet)		X	X	X	X
6	1	21		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X		X	X	(Outlet)		X	X	X	X
7	1	22		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X		X	X	(Outlet)		X	X	X	X
9	1	24-25	3rd	X	X	X	X	X	X	X	X	X	X					X	X	X	X
	2	(Night)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
10	1	25-26		X	X	X	X	X	X	X	X	X	X					X	X	X	X
	2	(Night)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
11	1	26-27		X	X	X	X	X	X	X	X	X	X					X	X	X	X
	2	(Night)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
12	1	27-28		X	X	X	X	X	X	X	X	X	X					X	X	X	X
	2	(Night)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
13	1	28-29		X	X	X	X	X	X	X	X	X	X					X	X	X	X
	2	(Night)		X	X	X	X	X	X	X	X	X	X					X	X	X	X
		29																			
14	1	Oct. 1	4th	X	X	X	X	X	X	X	X	X		X	X			X	X	X	X
	2	(Day)		X	X	X	X	X	X	X	X	X		X	X			X	X	X	X

LEGEND

ΔP Differential Pressure
SP Static Pressure
T Gas Temperature
GB Gauge Board Readings
CS Coal Samples
SV Secondary Voltage
IR In-Situ Resistivity
CN Condensation Nuclei
CL Climet Counter
ML Mass Loading
I Impactor
AS Ash Samples
SO_3 Gaseous SO_3

TABLE 25. MEASUREMENT METHODS

ITEM	MEASURED VARIABLE	SAMPLING METHOD	FREQUENCY	LOCATION	PURPOSE
1	Gas Concentrations	Time-Shared Gas Meas. Subsystem DuPont SO_2 Analyzer Bendix CO_2 Analyzer Beckman O_2 Analyzer MSA H_2O Vapor Analyzer	Continuous	Time Shared: Economizer Input ESP Output ESP	Determine molecular weight of gas; correlation of SO_2 and SO_3 concentrations; H_2O vapor concentration and conditioning of fly ash resistivity
		H_2O vapor by Silica Gel Method (Obtained during Mass Loading)	One/Run/Location	Input ESP Output ESP	
2	Gas Volume Flow	Flow Measurement Subsystem with Temp./Pres. Rakes	Continuous/Location	Economizer Stack	Determine mass flow of particulates and flue gases
		Manual Traverse (Obtained during Mass Loading)	One/Run/Location	Input ESP Output ESP	
3	Gauge Board Readings	Manual Recording of IP Instrumentation	Two/Run		Control and measurement of steam generator and ESP operating conditions
4	Coal Samples	Cyclone Collector	One/Run	Outputs of each Coal Mill (A, B, C, D)	Ultimate and proximate analysis to determine constituents including sulfur content
5	Secondary Voltage	Voltage Dividers and Precision Voltmeter	One/Hr.	Secondary of High Voltage Transformers	Measurement of Voltage-Current relationship
6	Fly Ash Resistivity	In-Situ Point-to-Plane Resistivity Probe	Two/Run	Input ESP	Effect of resistivity on ESP performance
7	Diffusional Particle Sizing (.01 μm-.15 μm)	Diffusion Battery and Condensation Nuclei Counter	One/Test	Input ESP Output ESP	Distribution and ESP efficiency versus particle size
8	Submicron Particle Sizing (0.4 μm-1.5 μm)	Climet Optical Particle Counter	One/Test	Input ESP Output ESP	Distribution and ESP efficiency versus particle size
9	Submicron Particle Sizing (0.3 μm- 5μm)	Brinks Impactor Andersen Model III Impactor	One/Run One/Run	Inlet ESP Outlet ESP	Mass distribution and ESP efficiency versus particle size
10	Mass Loading	Modified EPA Train In-Stack Thimble	One/Run One/Run	Inlet ESP Outlet ESP	Mass loading and overall ESP efficiency
11	Gaseous SO_3	Controlled Condensation with Adapted EPA SO_2 Train	One/Run/Location	Inlet ESP Outlet ESP	Measurement of SO_3 concentration and conditioning of fly ash resistivity
12	Ash Samples	Fly Ash obtained during Mass Loading	One/Run	Inlet ESP	Analysis of fly ash chemical composition; correlation with resistivity measurements

given in the MITRE publication, "Test Evaluation of Cat-Ox High Efficiency Electrostatic Precipitator," EPA-600/2-75-037.

Test Results

The Cat-Ox ESP has been designed to operate under normal operating conditions for the Unit 4 steam generator with an efficiency of 99.6 percent. Deviations from normal operating conditions will affect the ESP performance. Table 26 shows the results of the mass loading tests. Four of the 24 tests were subject to erroneous data as indicated in Table 26.

The results gathered from the tests can best be summarized in graphic form. Figures 14 through 19 show ESP performance vs. the various operating conditions investigated.

The operating conditions at Figure 14 are: load, 103 MW; flow, approximately 308,000 SCFM; coal, 3.58 percent sulfur. The figure indicates that efficiency is generally unaffected at current densities between 55 $\mu A/ft^2$ to 30 $\mu A/ft^2$. For current density below 30 $\mu A/ft^2$ collection efficiency decreases significantly. The penetration (1/collection efficiency) shows an increase by a factor of about 16 for a current density decrease of 3 times (i.e., penetration goes from 0.17 to 0.22 at 30 $\mu A/ft$ to from 2.69 to 3.82 at a current density of 10 $\mu A/ft$). Figure 15 (load-70 MW, flow 203,750) shows results similar to those found in the higher load tests. The efficiency remained constant from 55 $\mu A/ft^2$ to 30 $\mu A/ft^2$ and then decreased after 30 $\mu A/ft^2$. At this lower load (70 MW) an increase in

TABLE 26. ESP MASS LOADING AND EFFICIENCY AT VARIOUS OPERATING CONDITIONS

TEST RUN #	OPERATING CONDITIONS				LOCATION	MASS LOADING			EFFICIENCY
	LOAD	FUEL*	PLATE CURRENT	SPECIAL		GR/DSCF	GR/ACF	lb/HR	
2-1	103	HIGH SULFUR 3.54% wt.	AUTOMATIC (55 μA/ft^2)	SOOT BLOW	INLET OUTLET	1.6406 0.0148	0.9870 0.0092	3629.11 36.79	99.10
2-2					INLET OUTLET	1.6459 0.0089	0.9950 0.0054	4031.30 21.88	99.46
3-1	103	HIGH SULFUR 3.48% wt.	AUTOMATIC	4TH SECTION OFF	INLET OUTLET	1.3025 0.0208	0.8127 0.0128	2989.71 51.80	98.40
3-2					INLET OUTLET	1.2929 0.0159	0.8230 0.0098	2998.22 40.27	98.77
4-1	103	HIGH SULFUR 3.38% wt.	AUTOMATIC		INLET OUTLET	1.4312 0.0081	0.9118 0.0051	3247.51 20.14	99.43
4-2					INLET OUTLET	1.4748 0.0045	0.9168 0.0028	3333.57 11.54	99.70
5-1	103	HIGH SULFUR 3.44% wt.	20 μA/ft^2		INLET OUTLET	1.2860 0.0125	0.7987 0.0077	3085.08 31.37	99.03
5-2					INLET OUTLET	1.3086 0.0150	0.8057 0.0093	3061.56 38.25	98.85
6-1	103	HIGH SULFUR 3.46% wt.	10 μA/ft^2		INLET OUTLET	1.4489 0.0554	0.9033 0.0351	3246.70 141.91	96.18
6-2					INLET OUTLET	1.3277 0.0357	0.8179 0.0226	3118.33 94.23	97.31
7-1	103	HIGH SULFUR 3.67% wt.	30 μA/ft^2		INLET OUTLET	1.4020 0.0031	0.8649 0.0020	3106.46 8.08	99.78
7-2					INLET OUTLET	1.3687 0.0023	0.8226 0.0015	3056.38 6.23	99.83
9-1	85	HIGH SULFUR 3.56% wt.	AUTOMATIC		INLET OUTLET	2.3658 ---	1.4689 ---	4356.20 ---	(Leaky Probe)**
9-2					INLET OUTLET	1.4372 0.0140	0.9163 0.0087	2708.30 30.32	99.03 (88% Isokinetic)**
10-1	70	HIGH SULFUR 3.68% wt.	AUTOMATIC		INLET OUTLET	1.2311 0.0101	0.7600 0.0061	1931.38 15.48	99.18
10-2					INLET OUTLET	1.0265 0.0302	0.6426 0.0183	1626.41 47.48	97.06 (Green Filter)**
11-1	70	HIGH SULFUR 3.81% wt.	30 μA/ft^2		INLET OUTLET	1.1870 0.0088	0.7057 0.0054	1731.44 14.86	99.26
11-2					INLET OUTLET	1.2843 0.0351	0.7580 0.0216	1915.80 58.18	97.27 (Green Filter)**
12-1	70	HIGH SULFUR 3.75% wt.	20 μA/ft^2		INLET OUTLET	1.3063 0.0121	0.8049 0.0075	2089.63 20.11	99.07
12-2					INLET OUTLET	1.3465 0.0123	0.8096 0.0076	2130.74 19.91	99.09
13-1	70	HIGH SULFUR 3.60% wt.	10 μA/ft^2		INLET OUTLET	1.2982 0.0211	0.7706 0.0133	2038.85 34.73	98.38
13-2					INLET OUTLET	1.2161 0.0277	0.7190 0.0173	1812.58 47.70	97.72
14-1	103	LOW SULFUR 1.11% wt	AUTOMATIC		INLET OUTLET	0.9030 0.0038	0.5504 0.0023	2008.13 9.48	99.58
14-2					INLET OUTLET	0.8444 0.0049	0.5114 0.0030	1911.69 12.41	99.42

*Percentage of sulfur is shown on an as received basis. For coal analysis, see Table 12 and 13.

**Conditions which precluded computation of efficiency.

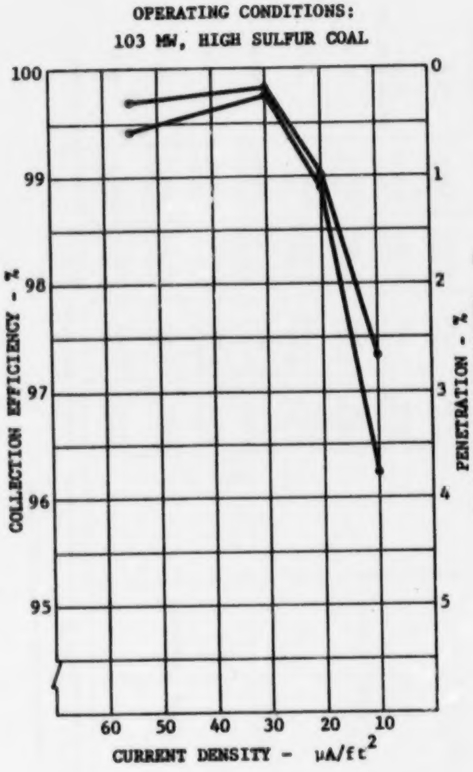

FIGURE 14
ESP EFFICIENCY VS.
CURRENT DENSITY

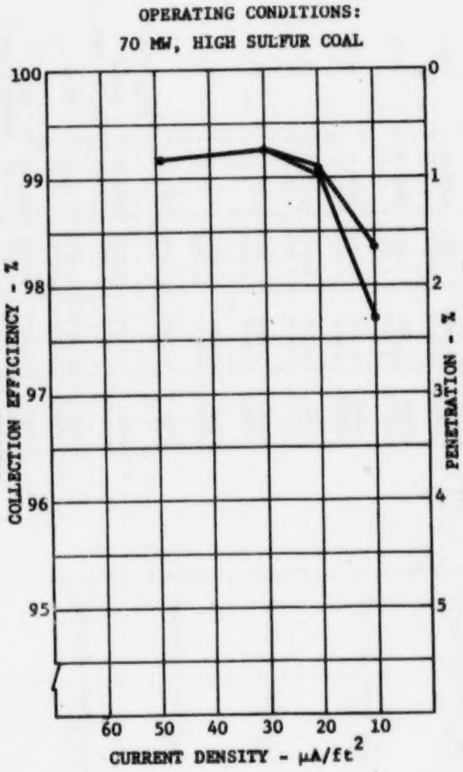

FIGURE 15
ESP EFFICIENCY VS.
CURRENT DENSITY

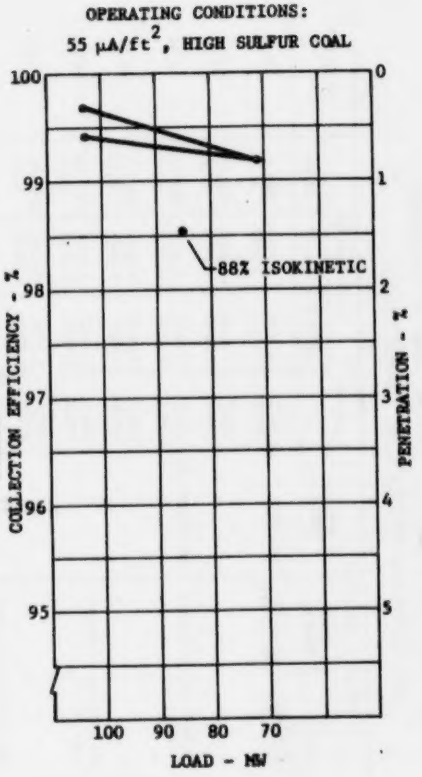

FIGURE 16
ESP EFFICIENCY
VS. LOAD

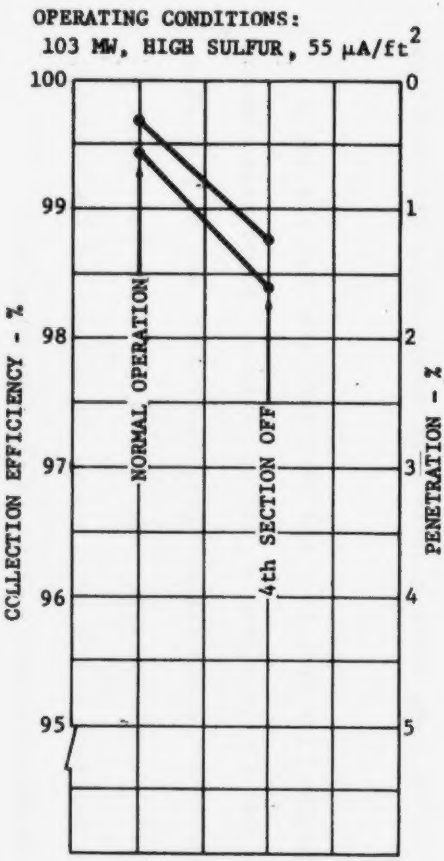

FIGURE 17
ESP EFFICIENCY WITH
4TH SECTION OFF

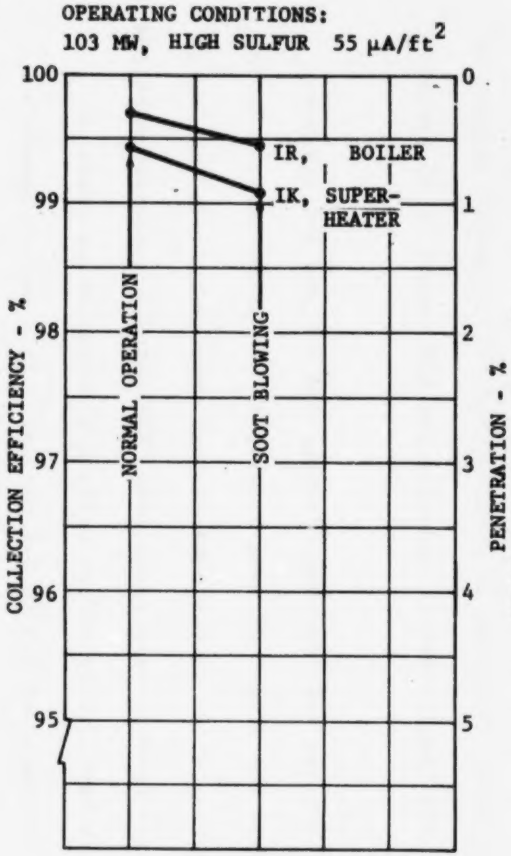

FIGURE 18
ESP EFFICIENCY DURING
SOOT BLOWING

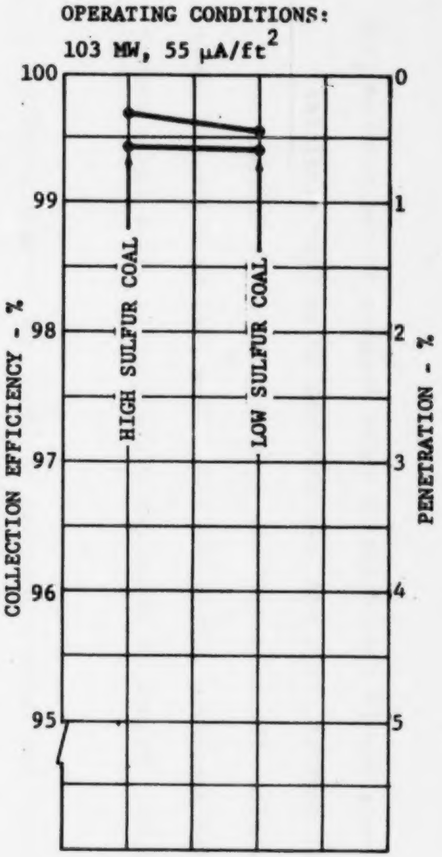

FIGURE 19
ESP EFFICIENCY FOR
LOW SULFUR COAL

ESP efficiency should theoretically exist because of the reduced flow in the ESP; however, this was only observed at current densities below 30 μA/ft. The data may have been influenced by unknown or uncontrolled phenomena within the ESP. This will be discussed later in the report. Figure 16 shows the efficiency vs. load for a number of loads.

Figure 17 indicates a decrease of about one percent in efficiency will occur (tripling of penetration) if the fourth section of the ESP is off (equivalent to reducing the ESP length by 25 percent, 10 feet).

Tests 4-1 and 4-2 (no soot blowing) and 2-1 and 2-2 are compared to show the effect of soot blowing in ESP performance. During 2-1, the retractables on the superheaters were energized; and during 2-2, the wall blowers were energized. The results indicated that the wall blowers have little effect while the retractables cause an efficiency decrease of 0.3 to 0.6 percent. This may represent a worse than normal case since blowers were continuously cycled during the test.

The results from test 14-1 and 14-2 indicate that the low sulfur coal had little effect on ESP efficiency. Since measurements showed no increase in ash resistivity, the results may be plausible. However, since experience with other low sulfur coals have shown a significant decrease in ESP efficiency, the effects of low sulfur coal were investigated again later in the test program.

The particle size distribution and fractional efficiency were investigated for particles below 5 μm. The measurements were performed using cascade impactors, a Climet optical particle counter and diffusion batteries with CN counters. A thorough discussion about sampling methods and procedure is given in "Test Evaluation of Cat-Ox High Efficiency Electrostatic Precipitation."

Table 27 and Figure 20 give the data obtained from the optical counter and the diffusion batteries (particle sizes between 0.01 μm and 0.15 μm). The data are presented as a function of efficiency and were determined by the equation

$$\frac{M_{Ii} - M_{Oi}}{M_{Ii}} = \text{Efficiency}$$

where

M_{Ii} = measured mass for size range i at the input of ESP.

M_{Oi} = measured mass for size range i at the output of ESP.

Table 28 gives the ESP efficiency vs. particle size for the impactor data. In general the efficiencies are lower than expected, which could be the result of some H_2SO_4 contamination. However, a mechanism by which contamination could occur could not be determined (see EPA-600/2-75-037). The particle size distribution obtained at the inlet and outlet is presented in Figures 21, 22 and 23. Again in comparing the outlet data with the optical counter, the impactor data seem to be contaminated. Figure 24 is the mass distribution from make up tests performed at the ESP inlet.

TABLE 27. FRACTIONAL EFFICIENCY FROM SRI DIFFUSIONAL AND OPTICAL DATA*

Test No.	3	4	5	6	7
Date	9/14	9/19	9/20	9/21	9/22
Power Supply Settings	Automatic 4th Section Off	Automatic	20 µA/ft^2	10 µA/ft^2	30 µA/ft^2
Size (µm)**	Efficiency %				
0.015	95	97.9	90	82	98.5
0.037	97.7	99.1	95.5	92.3	99.35
0.078	96.8	98.6	93.5	88	99
0.11	93.2	97.1	87	76	98
0.135	94	97.5	88	78	98.2
0.46	97.8	96.8	96.3	91.3	98.1
0.68	98.8	98.6	98.6	96.2	99.4
1.0	98.7	98.9	99.3	98.2	99.6
1.25	99.2	99.55	99.65	98.8	99.83
1.4	99.75	99.55	99.8	99.4	99.8
1.5	99	99.85	99.7	99.4	99.85

* Operating conditions: 103 MW, high-sulfur coal (3.49% weight average, as received, for tests indicated).

** Efficiency data in the size range 0.01 - 0.15 µm (diffusional data) are lower limits.

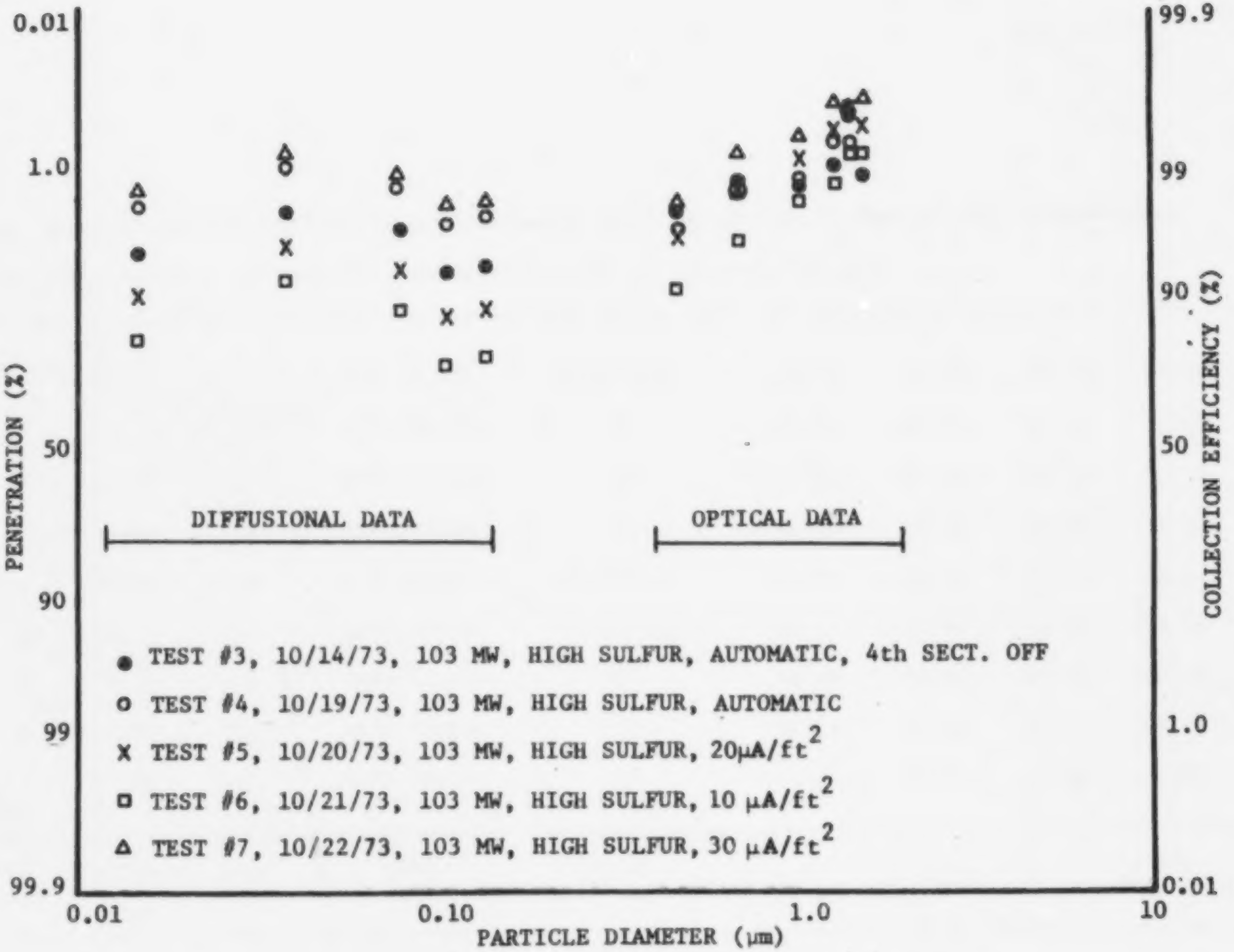

FIGURE 20
FRACTIONAL EFFICIENCIES FOR THE CAT-OX PRECIPITATOR

TABLE 28. FRACTIONAL EFFICIENCIES FROM MRI IMPACTOR DATA*

Test No.	Date	Load (MW)	Coal	Plate Current ($\mu A/ft^2$)	Particle Diameter, Geometric Mean (μm)** 4	2	1	0.8	0.4
5	9/20	103	High sulfur	20	97.05	96.08	91.89	90.03	85.44
6	9/21	103	High sulfur	10	87.91	89.92	85.73	84.44	85.61
7	9/22	103	High sulfur	30	98.89	97.97	96.90	95.80	91.73
9	9/25	85	High sulfur	Automatic	99.61	99.65	99.30	98.93	97.32
10	9/26	70	High sulfur	Automatic	99.04	98.02	96.39	95.11	89.33
11	9/27	70	High sulfur	30	97.96	97.75	94.78	92.67	82.67
12	9/28	70	High sulfur	20	99.28	97.95	97.08	95.71	88.65
13	9/29	70	High sulfur	10	99.24	98.26	94.51	93.14	98.66
14	10/1	103	Low sulfur	Automatic	98.79	98.19	95.79	95.15	94.33

* Data reduction for particle size distribution was performed by EPA.

** Efficiencies generally lower due to contamination of impactor stages by H_2SO_4 condensation.

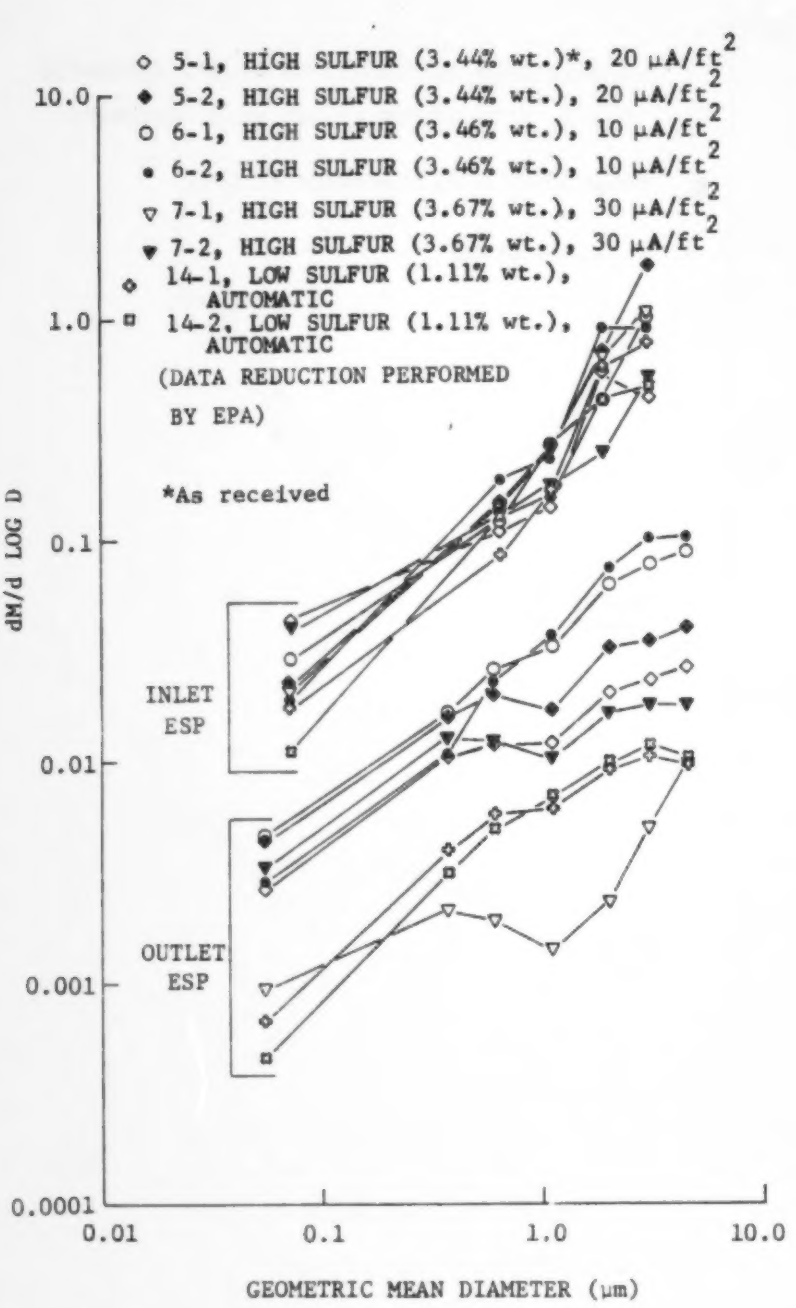

FIGURE 21
dM/d LOG D VERSUS GEOMETRIC MEAN DIAMETER FOR 103 MW LOAD TESTS

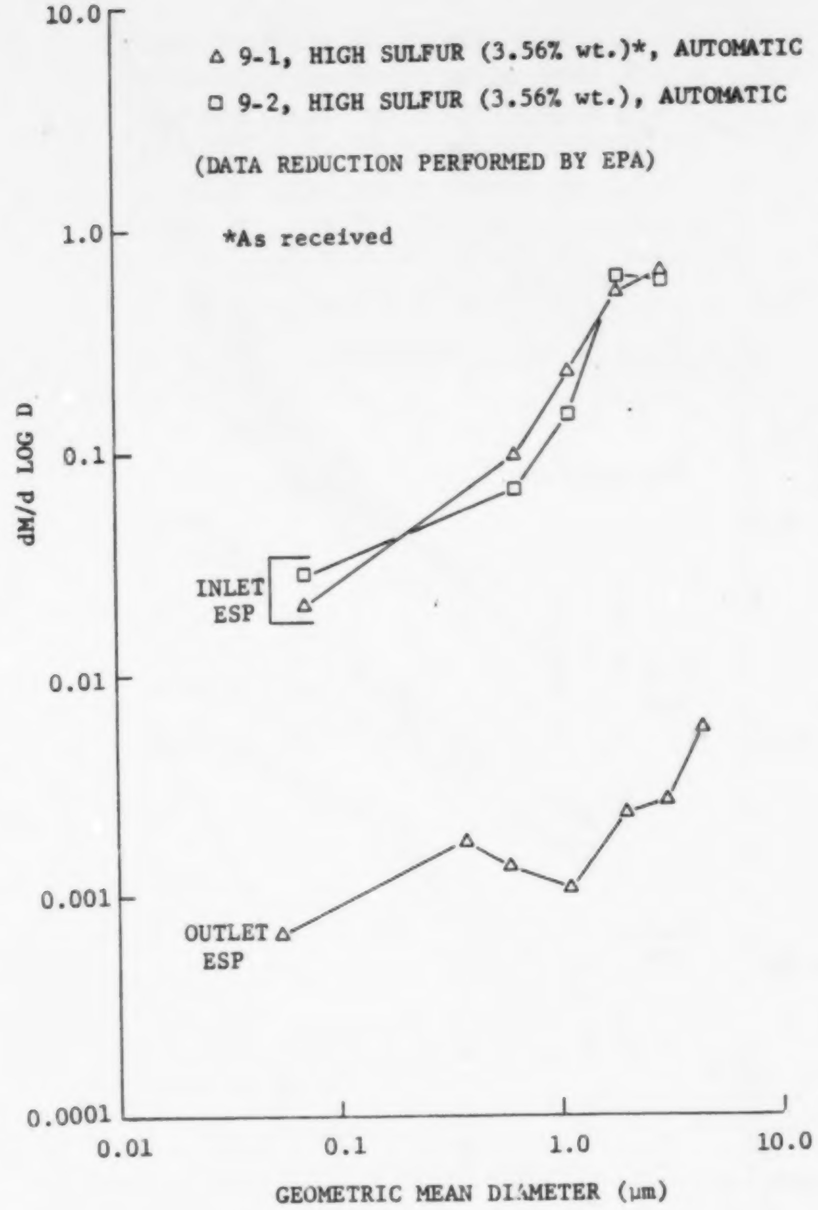

FIGURE 22
dM/d LOG D VERSUS GEOMETRIC MEAN DIAMETER FOR 85 MW LOAD TESTS

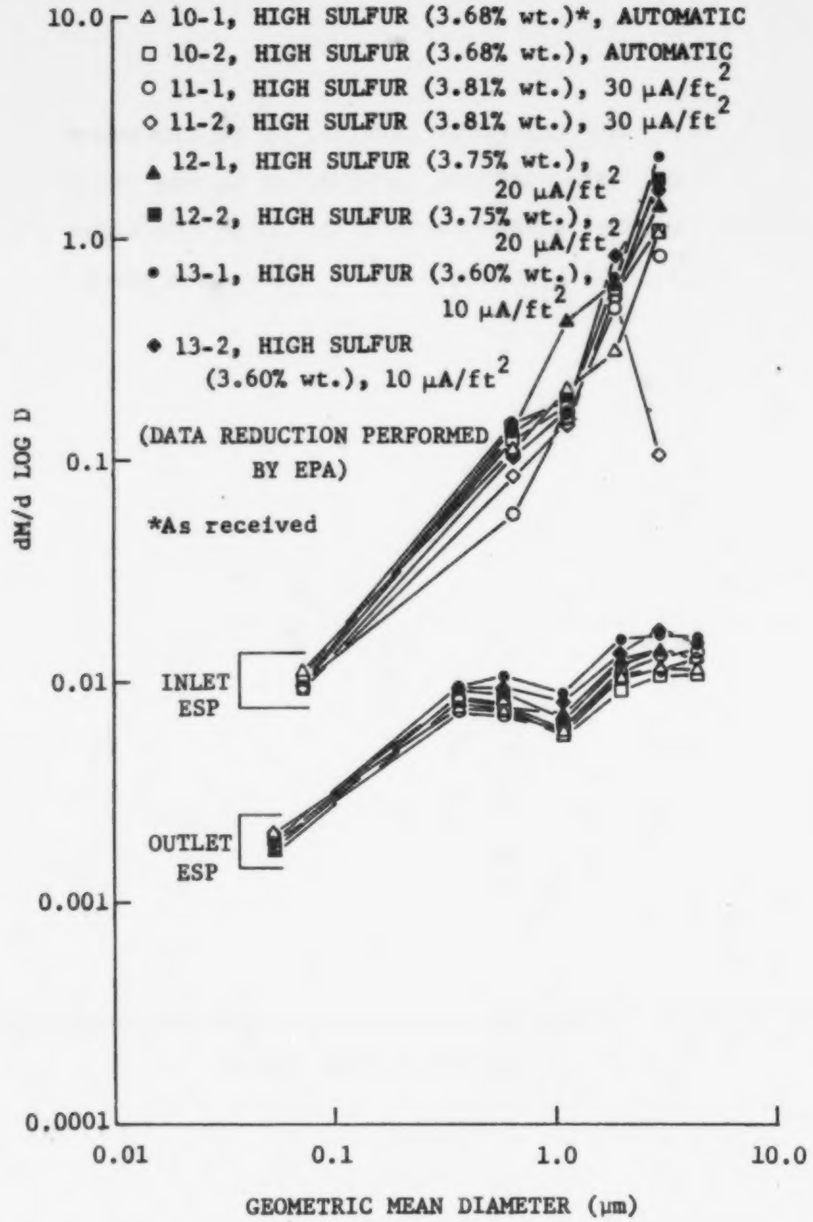

FIGURE 23
dM/d LOG D VERSUS GEOMETRIC MEAN DIAMETER FOR 70 MW LOAD TESTS

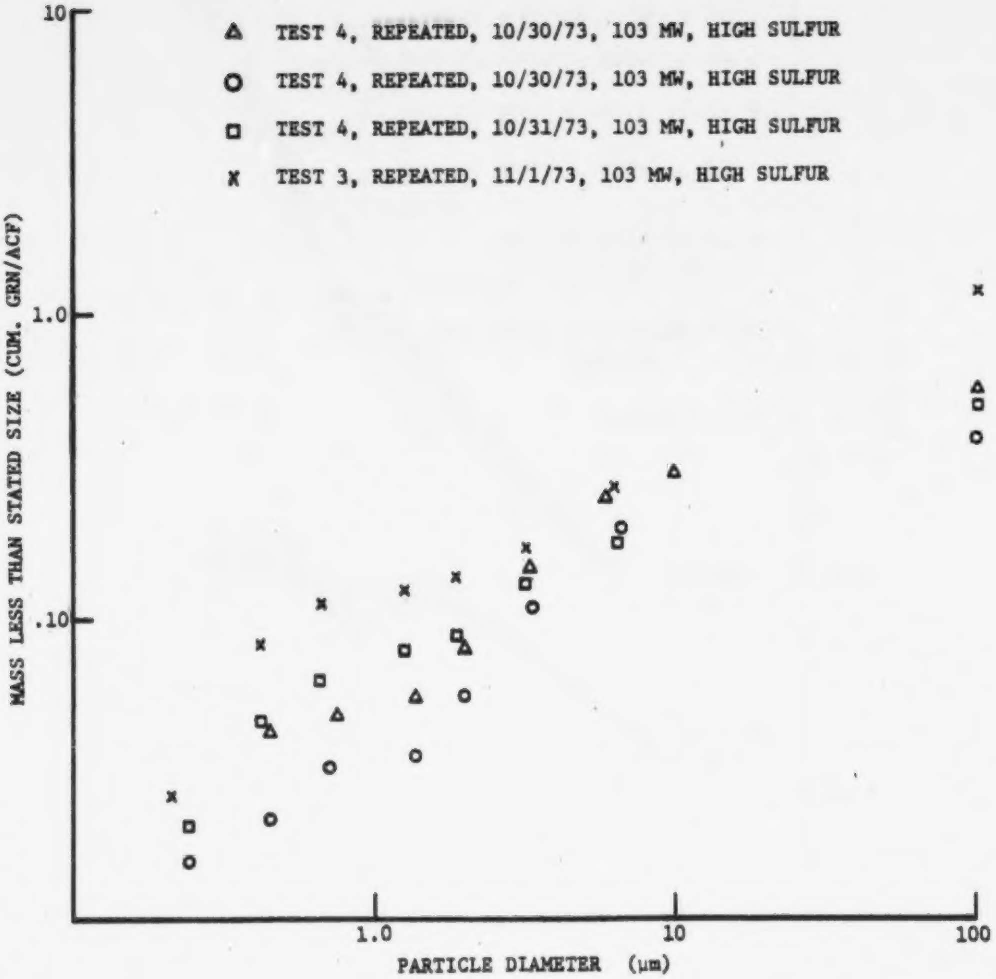

FIGURE 24
INLET MASS DISTRIBUTION CALCULATED FROM CASCADE IMPACTOR DATA

In situ resistivity measurements were performed by the parallel-disc measurement technique and the electric field-current density technique. The procedures and advantages of both methods are discussed in EPA-600/2-75-037.

Table 29 gives the SO_3 mass flow rates at the inlet and outlet of the ESP. In most tests, the SO_3 concentration was lower at the outlet of the ESP, implying that some mechanisms (possibly readsorbtion by fly ash) were removing SO_3. Table 30 shows the average values for SO_3 for the 103 MW high and low sulfur tests and the 70 MW high sulfur coal test.

Table 31 lists the results of the gas analysis during the tests. The SO_2 concentrations for the high sulfur coal averaged about 2,267 ppm and 424 ppm for the low sulfur coal. Table 32 compares the SO_3 and SO_2 concentrations in the gas. At the inlet SO_3 was approximately 0.7 percent of the SO_2 and at the outlet about 0.3 percent of the SO_2.

Water vapor measurments ranged from about 10 percent to 7 percent by volume averaging 9.2 percent at the inlet and 8.1 percent at the outlet.

The results of coal analysis (proximate and ultimate) are shown in Tables 33 and 34 on a "as received" and "dry" basis, respectively. The high sulfur coal averaged 3.58 percent S while the low sulfur coal was 1.11 percent S. The ash content was higher for the high sulfur coal than for the low sulfur coal. The chemical analysis of

TABLE 29. MEASURED SO_3 CONCENTRATION AND MASS FLOW

TEST NO.	LOCATION	OPERATING CONDITIONS				SO_3 CONCENTRATION		MASS FLOW (lb/Hr.)
		LOAD	COAL	SPECIAL	PLATE CURRENT	(PPM)	(lb/DSCF)	
2-1	INLET	103	HIGH SULFUR	SOOT BLOWING RETRACTABLES	AUTOMATIC	9.1	1.89×10^{-6}	29.27
	OUTLET					5.0*	1.02×10^{-6}*	17.72*
2-2	INLET	103	HIGH SULFUR	WALL BLOWERS	AUTOMATIC	--	--	--
	OUTLET					5.1*	1.05×10^{-6}*	18.14*
3-1	INLET	103	HIGH SULFUR	4th SECTION OFF	AUTOMATIC	27.9	5.78×10^{-6}	92.88
	OUTLET					5.6	1.16×10^{-6}	20.25
3-2	INLET	103	HIGH SULFUR	4th SECTION OFF	AUTOMATIC	47.7	9.86×10^{-6}	160.08
	OUTLET					3.5	$.71 \times 10^{-6}$	12.61
4-1	INLET	103	HIGH SULFUR	--	AUTOMATIC	21.1	4.36×10^{-6}	69.27
	OUTLET					8.1	1.68×10^{-6}	29.21
4-2	INLET	103	HIGH SULFUR	--	AUTOMATIC	15.8	3.27×10^{-6}	51.75
	OUTLET					.9	$.19 \times 10^{-6}$	3.91
5-1	INLET	103	HIGH SULFUR	--	20 μA/ft^2	2.9	$.59 \times 10^{-6}$	9.91
	OUTLET					15.4	3.18×10^{-6}	55.97
5-2	INLET	103	HIGH SULFUR	--	20 μA/ft^2	6.0	1.24×10^{-6}	20.31
	OUTLET					5.9*	1.23×10^{-6}*	21.90*
6-1	INLET	103	HIGH SULFUR	--	10 μA/ft^2	9.8	2.02×10^{-6}	31.69
	OUTLET					23.7	4.89×10^{-6}	87.76
6-2	INLET	103	HIGH SULFUR	--	10 μA/ft^2	13.0	2.70×10^{-6}	44.40
	OUTLET					1.7	$.35 \times 10^{-6}$	6.47
7-1	INLET	103	HIGH SULFUR	--	30 μA/ft^2	17.9	3.69×10^{-6}	57.24
	OUTLET					6.8*	1.4×10^{-6}*	25.79*
7-2	INLET	103	HIGH SULFUR	--	30 μA/ft^2	10.7	2.21×10^{-6}	34.40
	OUTLET					5.3	1.09×10^{-6}	20.51
9-1	INLET	85	HIGH SULFUR	--	AUTOMATIC	5.9*	1.21×10^{-6}*	15.60*
	OUTLET					4.7	$.98 \times 10^{-6}$	12.63
9-2	INLET	85	HIGH SULFUR	--	AUTOMATIC	4.7	$.97 \times 10^{-6}$	12.80
	OUTLET					6.4*	1.31×10^{-6}*	19.83*
10-1	INLET	70	HIGH SULFUR	--	AUTOMATIC	5.9*	1.23×10^{-6}*	13.51*
	OUTLET					5.1*	1.05×10^{-6}*	11.27*
10-2	INLET	70	HIGH SULFUR	--	AUTOMATIC	25.1	5.18×10^{-6}	57.46
	OUTLET					1.6	$.33 \times 10^{-6}$	3.63
11-1	INLET	70	HIGH SULFUR	--	30 μA/ft^2	18.5	3.83×10^{-6}	39.12
	OUTLET					6.1	1.26×10^{-6}	14.82
11-2	INLET	70	HIGH SULFUR	--	30 μA/ft^2	5.0	1.04×10^{-6}	10.86
	OUTLET					5.8*	1.20×10^{-6}*	13.92*
12-1	INLET	70	HIGH SULFUR	--	20 μA/ft^2	21.5	4.44×10^{-6}	49.73
	OUTLET					1.8	$.38 \times 10^{-6}$	4.44
12-2	INLET	70	HIGH SULFUR	--	20 μA/ft^2	8.7	1.81×10^{-6}	20.05
	OUTLET					5.6	1.16×10^{-6}*	13.11*
13-1	INLET	70	HIGH SULFUR	--	10 μA/ft^2	19.5	4.04×10^{-6}	44.42
	OUTLET					1.9	$.38 \times 10^{-6}$	4.37
13-2	INLET	70	HIGH SULFUR	--	10 μA/ft^2	7.8*	1.61×10^{-6}*	16.80*
	OUTLET					1.4	$.28 \times 10^{-6}$	3.37
14-1	INLET	103	LOW SULFUR	--	AUTOMATIC	4.4*	$.90 \times 10^{-6}$*	14.01
	OUTLET					5.4*	1.12×10^{-6}*	19.65*
14-2	INLET	103	LOW SULFUR	--	AUTOMATIC	9.3	1.93×10^{-6}	30.59
	OUTLET					2.9	$.60 \times 10^{-6}$	10.61

NOTE:
*At detectable limit of analytical method.

TABLE 30. AVERAGE SO_3 CONCENTRATIONS AND MASS FLOW

LOAD	COAL	LOCATION	SO_3 CONCENTRATION		SO_3 MASS FLOW
			(PPM)	(lb/DSCF)	(lb/Hr.)
103	HIGH SULFUR	INLET	16.5	3.4×10^{-6}	54.7
		OUTLET	8.0	1.7×10^{-6}	29.5
103	LOW SULFUR	INLET	9.3	1.9×10^{-6}	30.6
		OUTLET	2.9	0.6×10^{-6}	10.6
70	HIGH SULFUR	INLET	14.7	3.4×10^{-6}	36.9
		OUTLET	2.9	0.5×10^{-6}	6.1

TABLE 31. FLUE GAS COMPOSITION AT ECONOMIZER AND INPUT/OUTPUT OF ESP

Test Number*	Run Number	SO_2 Economizer (ppm)	SO_2 Input ESP (ppm)	SO_2 Output ESP (ppm)	CO_2 Economizer (%)	CO_2 Input ESP (%)	CO_2 Output ESP (%)	O_2 Economizer (%)	O_2 Input ESP (%)	O_2 Output ESP (%)	H_2O Economizer (%)	H_2O Input ESP (%)	H_2O Output ESP (%)
#2 9/13	#1 (10:03am-2:10pm)	2561	2405	1860	15.4	14.9	12.4	3.7	6.0	10.1	---	---	---
	#2 (3:30pm-7:45pm)	2535	2280	1725	15.2	14.3	11.9	3.7	5.6	10.3	---	---	---
#3 9/14	#1 (10:05am-1:13pm)	2276	2229	1525	15.1	13.9	11.4	4.3	6.2	11.7	---	---	---
	#2 (2:15pm-8:15pm)	2415	2235	1538	14.8	13.8	11.4	4.1	6.5	11.8	---	---	---
#15 9/15	Single Run (10:30am-5:30pm)	2370	2165	2250	15.7	14.0	11.0	3.8	5.7	10.8	--- ---	--- ---	--- ---
#8 9/19	Single Run	2490	2340	2295	15.3	---	14.7	3.8	---	5.8	---	---	---
#4 9/19	#1 (1:00pm-5:00pm)	2469	2310	2274	15.5	14.8	14.8	3.7	5.2	5.5	---	---	---
	#2 (6:57pm-9:35am)	2445	2235	2235	15.5	14.8	14.7	3.5	5.6	5.6	---	---	---
#5 9/20	#1 (9:56am-1:20pm)	2385	2190	2220	14.6	14.6	14.6	3.2	4.4	5.5	---	---	---
	#2 (2:20pm-6:45pm)	2325	2025	2138	15.0	14.2	14.2	3.7	5.8	5.6	---	---	---
#6 9/21	#1 (10:05am-12:32pm)	2325	2190	2190	----	----	----	4.0	5.0	5.4	5.5	---	5.1
	#2 (1:35pm-5:00pm)	2400	2175	2280	15.2	14.8	14.6	3.9	5.4	5.5	5.9	5.0	5.5
#7 9/22	#1 (9:50am-1:00pm)	2430	2250	2250	15.3	14.5	14.6	4.1	5.8	5.8	4.8	5.6	---
	#2 (2:00pm-5:00pm)	2400	2235	2235	15.2	14.5	14.5	4.2	5.9	5.8	6.2	5.2	5.6
#9 9/24-25	#1 (12:26am-3:05am)	2468	2280	2235	14.8	14.1	14.2	4.7	6.1	6.2	6.7	5.3	6.8
	#2 (4:20am-6:58am)	2520	2295	2295	----	14.5	14.5	4.5	6.1	6.2	7.2	---	5.8
#10 9/25/26	#1 (12:am-3:15am)	2430	2265	2325	14.5	14.7	14.6	4.2	5.7	5.6	5.2	4.9	5.1
	#2 (4:00am-7:02am)	2520	2305	2325	15.3	14.8	15.0	3.6	5.9	5.3	6.8	6.	6.1
#11 9/26-27	#1 (12:01am-4:00am)	2595	2370	2385	15.6	14.8	15.0	3.7	5.9	5.8	6.5	6.3	6.6
	#2 (4:15am-7:12am)	2655	2400	----	15.7	14.8	15.0	3.5	5.9	5.7	7.1	6.1	5.7
#12 9/27-28	#1 (12:00am-3:30am)	2685	2400	2355	14.3	14.7	14.2	3.6	5.7	6.0	8.2	6.5	6.5
	#2 (3:52am-6:55am)	2610	2400	2400	15.0	14.7	14.5	3.7	5.9	5.4	8.0	6.8	6.9
#13 9/28-29	#1 (12:00am-3:00am)	2505	----	2250	15.7	14.6	14.7	3.6	5.8	5.5	7.6	----	7.2
	#2 (3:55am-6:20am)	2385	2115	2175	15.5	14.7	14.9	3.6	5.8	5.6	7.9	6.6	---
#14 10/1	#1 (10:20am-1:20pm)	480	----	458	14.7	14.7	14.7	3.5	5.8	5.3	11.2	6.1	5.3
	#2 (1:55pm-3:57pm)**	420	390	----	14.9	14.5	14.2	4.0	5.5	5.8	7.3	6.4	6.8
#4 (R) 10/30	Single Run (1:15pm-4:15pm)	2618	2430	2400	15.5	14.8	14.8	3.5	5.5	5.6	6.7	7.1	7.0
#4 (R) 10/31	Single Run (10:00am-5:30pm)	2409	2205	2295	15.6	14.8	14.8	3.3	5.4	4.9	7.2	6.0	5.25
#3 (R) 11/1	Single Run (8:20am-12:35pm)	2559	2334	2175	15.6	14.6	14.4	3.3	5.4	5.0	7.1	7.7	7.8

TABLE 32. COMPARISON OF SO_3 AND SO_2 CONCENTRATIONS

TEST NO.	LOCATION	SO_3 CONCENTRATION (PPM)	SO_2 CONCENTRATION (PPM)	SO_3/SO_2 (Percent)
2-1	INLET	9.1	2405	0.4
	OUTLET	5.0*	--	--
2-2	INLET	--	2280	--
	OUTLET	5.1*	--	--
3-1	INLET	27.9	2229	1.3
	OUTLET	5.6	--	--
3-2	INLET	47.7	2235	2.1
	OUTLET	3.5	--	--
4-1	INLET	21.1	2310	0.9
	OUTLET	8.1	2274	0.4
4-2	INLET	15.8	2235	0.7
	OUTLET	0.9	2235	0.0
5-1	INLET	2.9	2190	0.1
	OUTLET	15.4	2220	0.7
5-2	INLET	6.0	2025	0.3
	OUTLET	5.9*	2138	--
6-1	INLET	9.8	2190	0.5
	OUTLET	23.7	2190	1.1
6-2	INLET	13.0	2175	0.6
	OUTLET	1.7	2280	0.1
7-1	INLET	17.9	2250	0.8
	OUTLET	6.8*	2250	--
7-2	INLET	10.7	2235	0.5
	OUTLET	5.3	2235	0.2
9-1	INLET	5.9*	2280	--
	OUTLET	4.7	2235	0.2
9-2	INLET	4.7	2295	0.2
	OUTLET	6.4*	2295	--
10-1	INLET	5.9*	2265	--
	OUTLET	5.1*	2325	--
10-2	INLET	25.1	2305	1.1
	OUTLET	1.6	2325	0.1
11-1	INLET	18.5	2370	0.8
	OUTLET	6.1	2385	0.3
11-2	INLET	5.0	2400	0.2
	OUTLET	5.8*	--	--
12-1	INLET	21.5	2400	0.9
	OUTLET	1.8	2355	0.1
12-2	INLET	8.7	2400	0.4
	OUTLET	5.6*	2400	--
13-1	INLET	19.5	--	--
	OUTLET	1.9	2250	0.1
13-2	INLET	7.8*	2115	--
	OUTLET	1.4	2175	0.1
14-1	INLET	4.4*	--	--
	OUTLET	5.4*	458	--
14-2	INLET	9.3	390	2.4
	OUTLET	2.9	--	--

TABLE 33. PROXIMATE AND ULTIMATE COAL ANALYSIS--AS RECEIVED BASIS

Test Number	ULTIMATE ANALYSIS					PROXIMATE ANALYSIS				
	Carbon (% Wt.)	Hydrogen (% Wt.)	Nitrogen (% Wt.)	Sulfur (% Wt.)	Oxygen (% Wt.)	Moisture (% Wt.)	Ash (% Wt.)	Volatile Matter (% Wt.)	Fixed Carbon (% Wt.)	Heat of Combustion (Btu/lb)
2	66.23	5.12	0.99	3.54	13.26	3.62	10.86	37.56	47.96	12,114
3	67.96	4.67	1.06	3.48	12.76	3.65	10.07	37.86	48.42	12,096
4	66.90	5.24	1.02	3.38	12.32	3.69	11.14	37.73	47.44	12,113
5	66.36	5.04	1.03	3.44	13.03	3.77	11.10	37.54	47.59	12,006
6	66.83	5.18	1.02	3.46	12.95	4.02	10.56	37.84	47.58	12,077
7	66.24	5.19	1.09	3.67	13.34	4.21	10.47	38.20	47.12	12,136
8	66.11	5.13	0.99	3.62	12.76	3.61	11.39	37.49	47.51	11,991
9	66.84	5.21	0.95	3.56	13.13	4.10	10.31	38.35	47.24	12,088
10	66.87	5.26	0.99	3.68	12.83	3.60	10.37	38.19	47.84	12,202
11	67.05	5.26	0.89	3.81	12.59	3.61	10.40	38.01	47.98	12,211
12	66.54	5.23	0.99	3.75	12.59	3.50	10.90	37.82	47.78	12,065
13	67.05	5.11	1.00	3.60	12.84	3.55	10.40	37.91	48.14	12,210
14	72.71	5.48	1.21	1.11	13.04	4.19	6.45	34.48	54.88	12,813
15	67.25	5.16	0.99	3.51	12.73	3.65	10.36	38.06	47.93	12,066

Average High Sulfur = 3.58% by weight

Average High Sulfur Ash = 10.64% by weight

TABLE 34. PROXIMATE AND ULTIMATE COAL ANALYSIS--DRY BASIS

	ULTIMATE ANALYSIS					PROXIMATE ANALYSIS			
Test Number	Carbon (% Wt.)	Hydrogen (% Wt.)	Nitrogen (% Wt.)	Sulfur (% Wt.)	Oxygen (% Wt.)	Ash (% Wt.)	Volatile Matter (% Wt.)	Fixed Carbon (% Wt.)	Heat of Combustion (Btu/lb)
2	68.72	4.90	1.03	3.67	10.41	11.27	38.97	49.76	12,569
3	70.53	4.43	1.10	3.61	9.88	10.45	39.29	50.26	12,554
4	69.46	5.02	1.06	3.51	9.38	11.57	39.18	49.25	12,577
5	68.96	4.80	1.07	3.57	10.05	11.55	39.01	49.44	12,476
6	69.63	4.93	1.06	3.60	9.78	11.00	39.42	49.58	12,583
7	69.15	4.93	1.14	3.83	10.02	10.93	39.88	49.19	12,669
8	68.59	4.91	1.03	3.76	9.89	11.82	38.89	49.29	12,440
9	69.70	4.96	0.99	3.71	9.89	10.75	39.99	49.26	12,605
10	69.37	5.04	1.03	3.82	9.98	10.76	39.62	49.62	12,658
11	69.56	5.04	0.92	3.95	9.74	10.79	39.43	49.78	12,668
12	68.95	5.02	1.03	3.89	9.81	11.30	39.19	49.51	12,502
13	69.52	4.89	1.04	3.73	10.04	10.78	39.31	49.91	12,659
14	75.89	5.23	1.26	1.16	9.73	6.73	35.99	57.28	13,373
15	69.80	4.93	1.03	3.64	9.85	10.75	39.50	49.75	12,523

Average High Sulfur = 3.72% by weight

Average High Sulfur Ash = 11.06% by weight fly ash for certain critical elements and total sulfates is presented in Table 35.

The SRI ESP computer systems model was utilized to project the variation in efficiency expected for a variation in volume flow rate. The results of the computer simulation with the experimental data superimposed are shown in Figure 25 for the four levels of current density employed in the test program. The computer simulation curves are based on the Deutch exponential collection efficiency equation, which has been substantiated experimentally for ideal operating conditions. The field measured data for the 10 $\mu A/ft^2$ current density approximates the theoretical curve; however, as the current density is increased, the field measured data systematically deviate from the theoretical curves such that the efficiencies at the larger gas volume flow rates become higher than at the smaller gas volume flow rates. The implication is that the computer simulation program does not account for some of the phenomena that could cause slight changes in efficiency at the high levels of performance being obtained. These phenomena are complex and may possibly be related to the effect of ion density on the electric field, diffusion charging, and non-uniform gas flow.

The computer model does not include factors to account for particle re-entrainment. Therefore, the model is primarily useful for extrapolating the gross behavior of precipitators, rather than for predicting the absolute efficiency of a particular ESP unit. The

TABLE 35. CHEMICAL CONTENT OF FLY-ASH SAMPLED AT ESP INLET

Test Number	C (% Wt)	H (% Wt)	N (% Wt)	Al (% Wt)	Ca (% Wt)	Fe (% Wt)	Li (% Wt)	Mg (% Wt)	K (% Wt)	Si (% Wt)	Na (% Wt)	Sulfate (% Wt)
2	2.76	0.39	0	6.7	1.73	9.0	0.0071	0.045	1.22	11.6	0.29	3.2
3	2.21	0.12	0	6.5	1.76	8.3	0.0071	0.029	0.99	11.4	0.39	1.7
4	1.63	0.70	0	6.4	1.90	8.2	0.0077	0.038	1.22	12.0	0.52	2.8
5	1.28	0.51	0	8.2	2.46	7.9	0.0074	0.062	1.29	12.6	0.48	2.8
6	3.09	0.36	0	8.2	2.29	8.0	0.0063	0.052	1.21	12.7	0.39	3.7
7	1.14	0.40	0	10.4	0.58	8.1	------	0.049	1.15	15.1	0.65	---
9	1.94	0.60	0	8.4	2.15	9.5	0.0070	0.053	1.36	13.6	0.42	3.0
10	2.20	0.70	0	8.5	2.23	9.7	0.0075	0.058	1.44	13.1	0.41	5.2
11	1.06	0.46	0	6.6	1.80	9.3	0.0074	0.043	1.13	12.2	0.37	3.7
12	0.75	0.61	0	6.8	1.72	9.6	0.0068	0.046	1.30	13.5	0.37	4.6
13	1.50	0.35	0	7.9	1.82	9.0	0.0054	0.043	1.19	12.9	0.29	7.1
14	3.74	0.47	0	9.5	1.42	4.7	0.0086	0.041	1.37	12.6	0.27	1.7

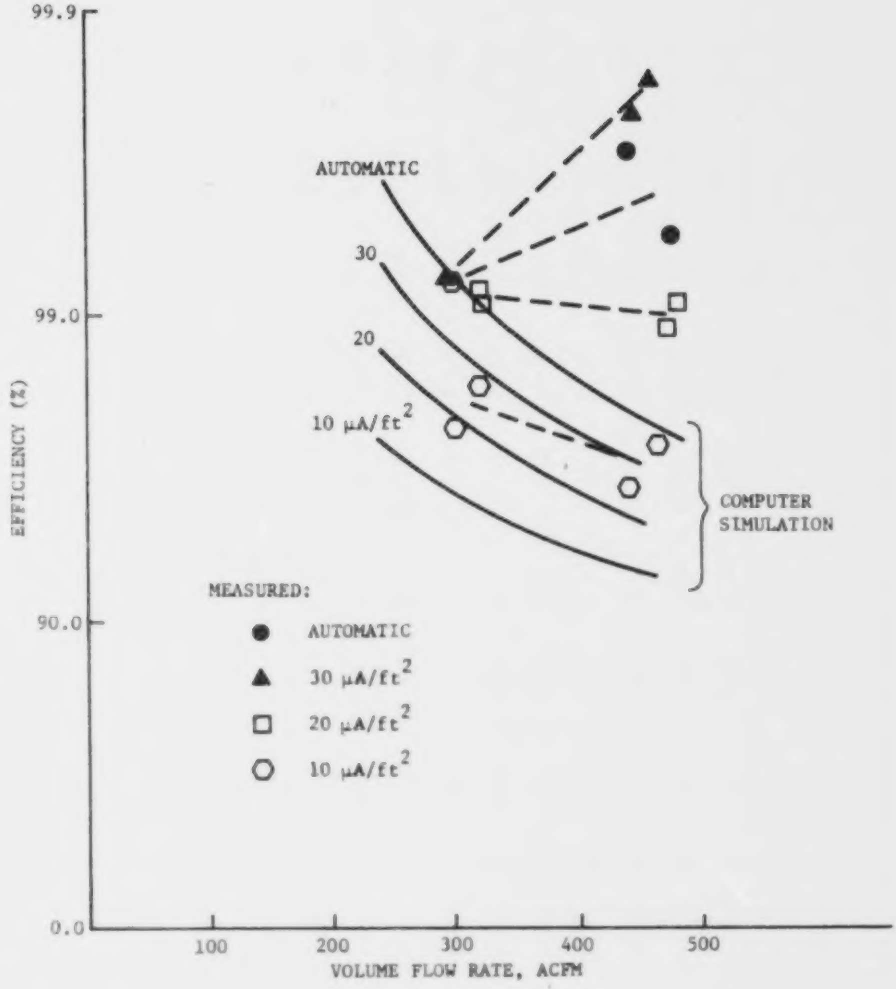

FIGURE 25
COMPARISON OF COMPUTER SIMULATED AND MEASURED ESP EFFICIENCIES

result of neglecting re-entrainment primarily influences the computed versus measured performance in the particle sizes greater than 1 μm. Therefore, the computer simulation for 10, 20, and 30 microamperes per square foot was run for size-fractional efficiencies in this range. The results of this simulation are shown, together with the size-fractional efficiency as determined by measurement, in Figures 26, 27, and 28. The break in the predicted simulation curve results from the unavailability of a suitable theory to explain the transition from the region where field charging dominates to the region where diffusional charging dominates. In the lower limit region of the measured data, the experimental points represent the lowest possible level of efficiency. Consequently, the measured data in this region are not a true measure of the efficiency and have been connected to the optically measured data to show, in general, that the form of the curve agrees with theory.

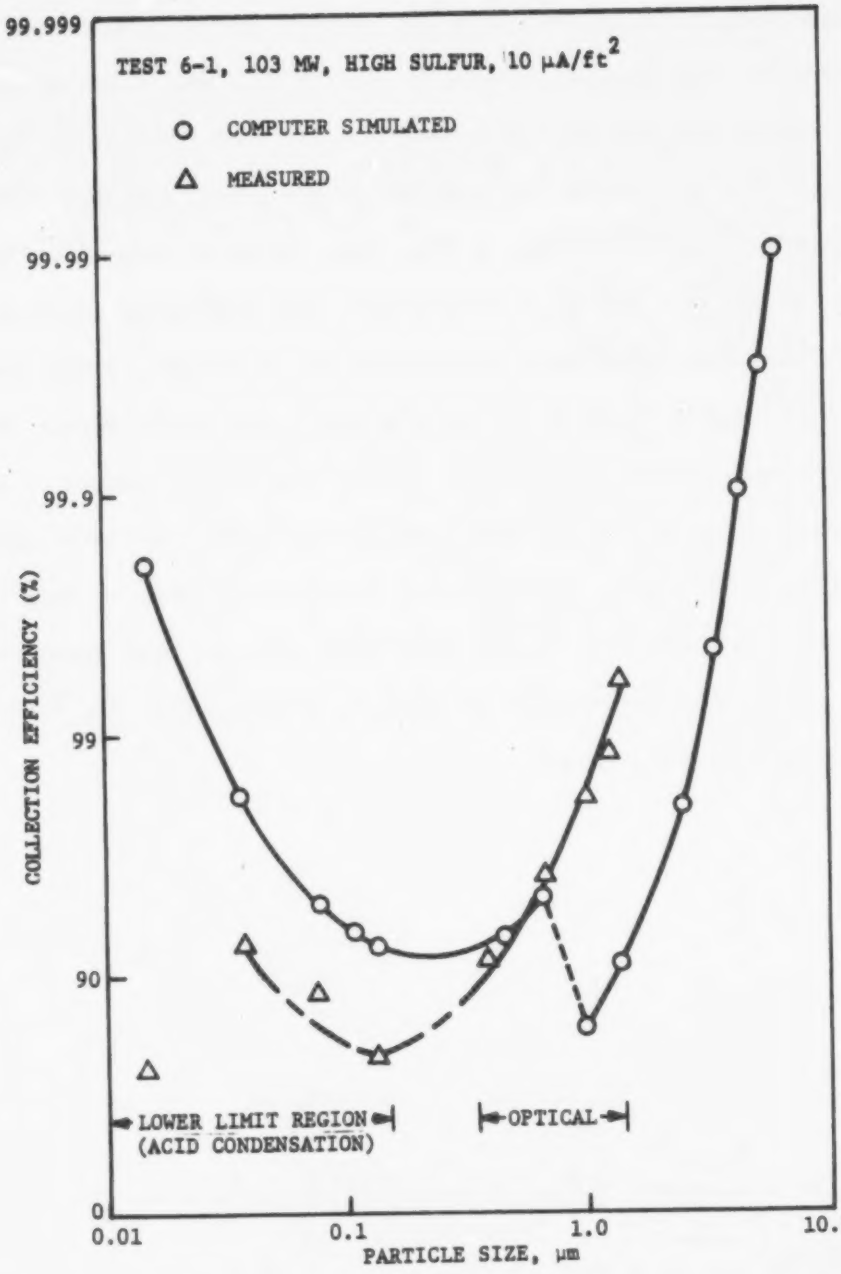

FIGURE 26
COMPARISON OF COMPUTED AND MEASURED SIZE FRACTIONAL EFFICIENCIES FOR 10 MICROAMPERES PER SQUARE FOOT CURRENT DENSITY

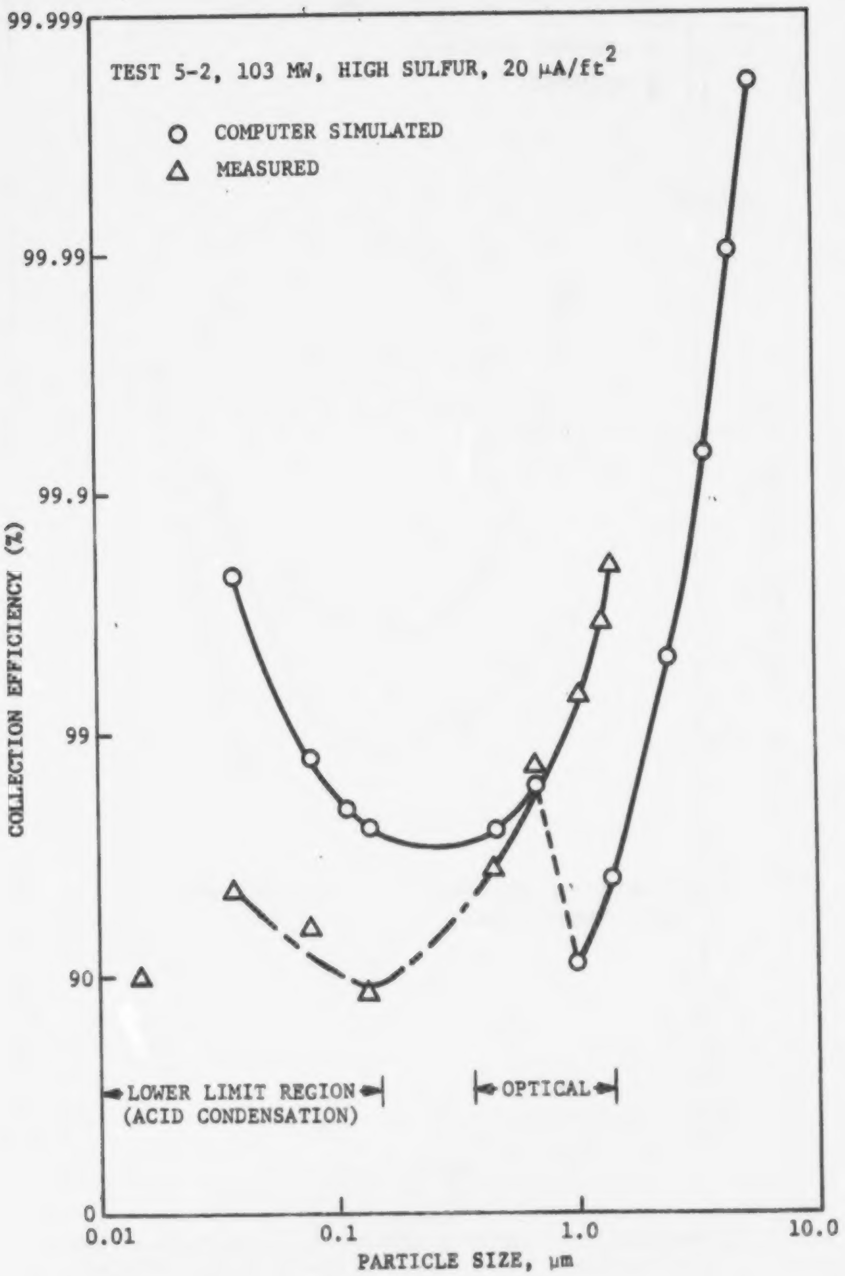

FIGURE 27
COMPARISON OF COMPUTED AND MEASURED SIZE FRACTIONAL EFFICIENCIES FOR 20 MICROAMPERES PER SQUARE FOOT CURRENT DENSITY

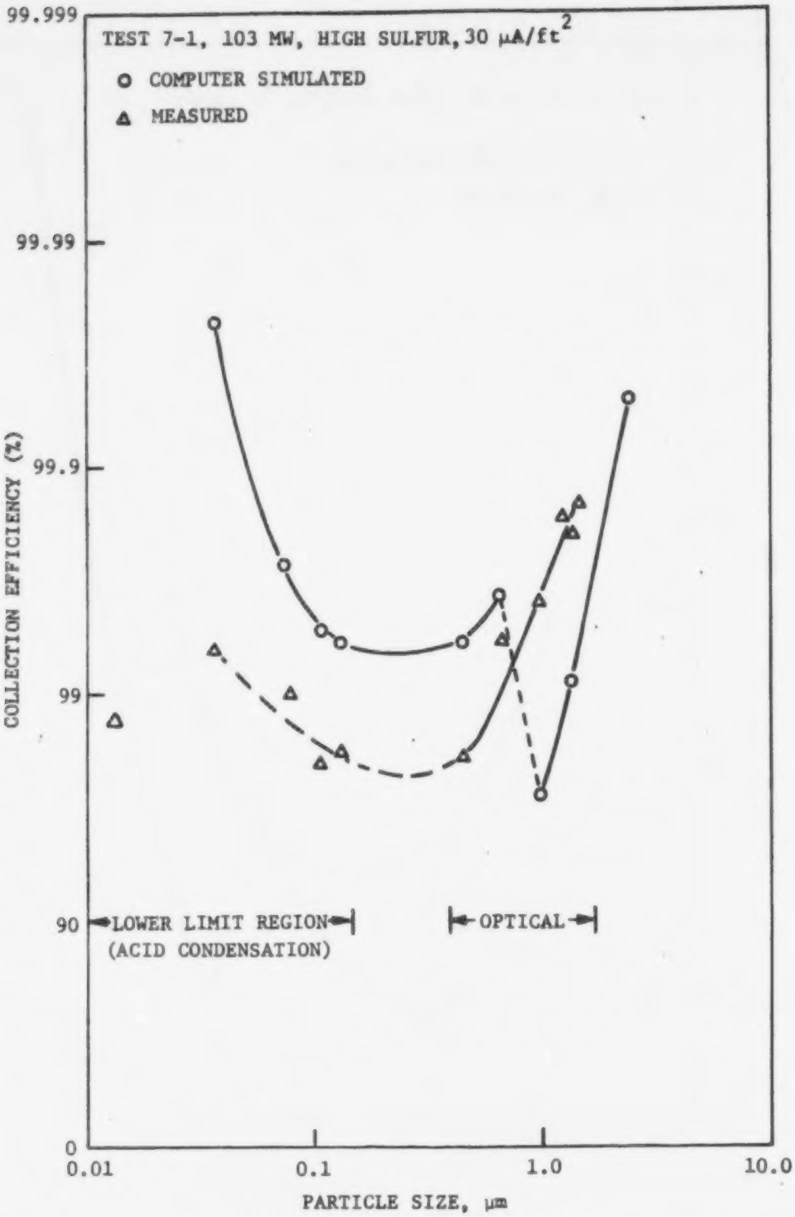

FIGURE 28
COMPARISON OF COMPUTED AND MEASURED SIZE FRACTIONAL EFFICIENCIES FOR 30 MICROAMPERES PER SQUARE FOOT CURRENT DENSITY

Conclusion

In the normal mode of operation for the Unit 4 steam generator (i.e., 103 MW load, high-sulfur coal, and ESP functioning automatically), the total ESP efficiency was measured to be in the 99.43 to 99.70 percent range, indicating that the ESP was operating either at or close to the design efficiency (99.6 percent). A change to low-sulfur coal (1.11 percent S, as received) under these same operating conditions showed no significant loss in efficiency.

A decrease in load from 103 MW to 70 MW, with a corresponding decrease in gas volume flow from an average of 308,000 SCFM to 203,750 SCFM, resulted in a decrease of ESP efficiency as opposed to the expected increase in efficiency. An explanation of this result cannot be made based on the available data; more data are required, particularly at the lower load levels, to provide a definitive statistical result.

The ESP efficiency is nearly constant for ESP current densities from 55 $\mu A/ft^2$ (automatics) to 30 $\mu A/ft^2$. As current densities decreased below 30 $\mu A/ft^2$ collection efficiency begins to drop, reaching a value ranging from 96.18 percent to 97.31 percent at a current density of 10 $\mu A/ft^2$. Resulting fly ash penetration (1/collection efficiency) increases to values of from 2.69 percent to 3.82 percent at 10 $\mu A/ft^2$ from values of 0.17 percent to 0.22 percent at 30 $\mu A/ft^2$. Therefore, on the average, penetration increased by a factor of approximately 16 for a factor of 3 decrease in current density.

With the fourth section of the ESP off, a loss in efficiency of one percent with a corresponding tripling of the fly ash penetration was observed. This result shows the effect of having a smaller precipitator, shorter in length by approximately 10 feet (25 percent of total length).

Soot blowing using only the wall blowers had no discernible effect on ESP efficiency or outlet grain loading; however, soot blowing using the retractable blowers dropped the efficiency by 0.3 to 0.6 percent and caused approximately a doubling of the fly ash penetration.

The data involving measurement of particle size efficiency resulted in some difficulties. One problem was contamination of impactor data at the precipitator outlet by condensation of H_2SO_4. In addition, similar contamination was observed in the condensation nucleii (CN) apparatus; however, good results were obtained with the Climet optical counter in the 1.5 μm to 0.46 μm size range. A drop in efficiency from 99.85 to 96.80 percent from the large particle size to the small particle size was determined for the ESP in the automatic mode of operation.

Even though the CN results were contaminated by H_2SO_4 condensation, a lower limit of efficiency was determined in the diffusional size of range from 0.01 μm to 0.15 μm. The ESP efficiency was greater than 97 percent over this range.

The resistivity measurements of the low-sulfur coal were approximately the same as for the high-sulfur coal, corroborating the high ESP efficiency obtained during the low-sulfur coal test. The resistivity may have been dominated by surface conductivity in the presence of high concentrations of water vapor and SO_3.

The ESP efficiencies determined from the measured data were compared with efficiencies determined by the SRI ESP computer systems model. In a comparison of total efficiency versus gas volume flow, the measured data verified the validity of the simulation model at the lower current densities, but deviated from the model at the higher current densities. Comparisons were also made of measured fractional efficiencies and computed efficiencies. There was general agreement between the measured and computed data.

This series of tests left two unexplained deviations from the expected results. First, the low sulfur coal was expected to reduce ESP efficiency and did not. Though the resistivity of the ash was similar to high sulfur coal ash a possible reason why no reaction was noted could be due to insufficient operating time on the ESP. On subsequent tests, it was noted that a period of several hours was required to purge the ESP system of residual ash material when the fuel type was changed. Further investigations of this possibility are discussed in the special test section of this report.

Another area was the decrease in efficiency with decrease in load for the higher current densities. The anticipated results may have been obscured by the loss of data points and the need to obtain sufficient data to indicate a statistical trend. Conversely, existing analytical expressions do not define all of the significant phenomena occurring in commercial precipitators. The possible causes for the decrease in efficiency are further discussed in the Special Tests portion of Section V.

Main Test Program

The main test program was to be a series of test groups that entailed the comprehesive testing of the Cat-Ox overall system and its sub-system. Table 36 gives a summary of the main test program. The specific details and description of the individual tests are outlined in "Test Plan for Cat-Ox Demonstration" MITRE document M76-24. Only one group of tests (on the electrostatic precipitator) was completed since the Cat-Ox system remained inoperable during the extent of the contract. The Transient Test Program (integrated into the main steady state test program) is discussed in the next section.

Test Objective--This series of electrostatic precipitation tests was to be the first in a program of approximately 18 tests series (the main test program) which were designed to determine the performance characteristics of the total Cat-Ox. The entire program along with specific details on this test is outlined in "Test Plan for Cat-Ox Demonstration" MITRE document M76-24. The main objective was to test the Cat-Ox ESP subsystem to determine if it was performing as designed and to quantify its performance under a range of conditions.

TABLE 36. SUMMARY OF TEST PROGRAM DESIGN

T ESP-2-1

SUBSYSTEM	TIME PERIOD (WEEKS)	NUMBER OF TESTS	DESIGN	STEAM GENERATOR VARIABLES
Electrostatic Precipitator	2½	12	Full Factorial	Load, fuel, soot blowing
No test (Cat-Ox Process Start-Up)				
Converter, Heat Exchanger		3	Fractional Factorial I	Load, excess air
Heat Exchanger Soot Blowing	1	1	Special	
No Testing	1			
Absorbing Tower	1	3	Random Complete Block	Load
Heat Exchanger Soot Blowing	1	1	Special	
Converter, Heat Exchanger		1	Fractional Factorial II	Load, excess air
No Testing	1			
Mist Eliminator Wash	1	1	Special	
Absorbing Tower		3	Random Complete Block	Load
Converter, Heat Exchanger	1	3	Fractional Factorial III	Load, excess air
No Testing- Steam Generator Cat-Ox Process Maintenance (Catalyst cleaning, Heat Exchanger Wash)	1			
Converter, Heat Exchanger	1	3	Fractional Factorial I	Load, excess air
Mist Eliminator	1	1	Special	
Absorbing Tower		3	Random	Load
No Testing	1			
Mechanical Collector, Precipitator and Overall System (Particulate)	1	3	Special	Load
Converter, Heat Exchanger	1	3	Special	Load
No Testing (Catalyst Cleaning)	2		Fractional Factorial II	Load, excess air
Converter, Heat Exchanger	1	3	Fractional Factorial II	Load, excess air
No Testing	1			
Overall System	1½	6	Fractional Factorial I	Load, fuel, excess air
No Testing	2½			
Overall System	1½	6	Fractional Factorial II	Load, fuel, excess air
No Testing	2			
Overall System	1½	6	Fractional Factorial III	Load, fuel, excess air

No other tests in the main test program were completed since the Cat-Ox one-year demonstration was never initiated.

Schedule--Table 37 shows a list of the tests and desired conditions for each test. There were three variables: load, fuel, soot blowing. The load to be set at 100 MW, 80 MW and 60 MW for four tests each while fuel type and soot blowing were varied. The test was originally designed for high and low sulfur fuels; however, due to the lack of low sulfur coal a mixture of gas and coal was employed. Excess air was to be set at 4.0 percent 0_2 and burner angle was normal.

Particle sampling at the input and output of the ESP was performed by personnel from the Midwest Research Institute while test coordination, continuous gas analysis and coal sampling was performed by MITRE personnel.

A total of 15 tests were run; only 12 were required. The three extra tests had to be run to repeat tests 1, 6 and 11.

The test schedule was modified for the following reasons: test 1 was repeated because a particulate matter sampling line broke during the first test. Tests 6 and 11 were repeated because the sampling filters were found to be contaminated. This was probably the result of ambient air cooling the filter below the dew point. Table 38 shows the actual test schedule including the extra tests. As can be seen from the table, the schedule was rearranged to fit into Illinois

TABLE 37. ELECTROSTATIC PRECIPITATOR (ESP) TESTS

PURPOSE	DESIGN PERFORMANCE	MEASURED PARAMETERS & OPERATIONAL INTEGRITY	MONITORING & ANALYSIS	SUBSYSTEM OPERATING STATUS
CHANGE OF EFFICIENCY AND OUTPUT GRAIN LOADING VS. TIME	99.67% .005 GRAINS/STANDARD CUBIC FOOT, 32°F	MASS FLOW OF PARTICULATE - POINTS 1, 3	PERIODICALLY	SCHEDULED MAINTENANCE OF ESP - BEFORE AND AFTER
CHANGE OF ELECTRICAL CHARACTERISTICS VS. TIME	TEST SETTINGS AS SPECIFIED BY ILLINOIS POWER COMPANY	PRIMARY VOLTAGE PRIMARY CURRENT SECONDARY CURRENT	RECORD PERIODICALLY	
CHANGE OF ELECTRO-MECHANICAL CHARACTERISTICS VS. TIME	TEST SETTINGS AS SPECIFIED BY ILLINOIS POWER COMPANY	INTEGRITY OF DISCHARGE ELECTRODES OPERATION OF ELECTRODE VIBRATORS, FREQUENCY AND INTENSITY OPERATION OF PLATE RAPPERS, FREQUENCY AND INTENSITY OPERATION OF HOPPER LEVEL INDICATORS OPERATION OF HOPPER VIBRATORS	RECORD PERIODICALLY	
CORROSION	TEMPERATURE - 310°F	MATERIALS, POINT 3 - C-1008 CARBON STEEL, 316 STAINLESS STEEL, COR-TEN	CORROSION RATES	
		TEMPERATURE, POINT 3	MONITOR TEMPERATURE	

TABLE 38. ESP SUBSYSTEM TEST SCHEDULE

Test No.	Date	Excess Air	Load	Fuel	Soot Blowing	Comment
12	9/12/74	4%	100	Coal	Yes	
1	9/13/74	4%	100	Coal	No	
9	9/15/74	4%	80	Coal	No	ESP Noisy
11	9/16/74	4%	60	Coal	No	Green Filter
5	9/17/74	4%	80	Coal	Yes	
6	9/18/74	4%	60	Coal	Yes	Green Filter
4	9/19/74	4%	80	Coal/Gas	No	
7	9/22/74	4%	80	Coal/Gas	Yes	
6R 11R	9/23/74	4%	60	Coal	Yes No	Repeat for 6 and 11
10 8	9/24/74	4%	60	Coal/Gas	No Yes	
2	9/26/74	4%	100	Coal/Gas	No	
3	9/27/74	4%	100	Coal/Gas	Yes	

Power Company's schedule so as to produce a minimal amount of interference with normal operation.

Originally, the sulfur content of the fuel was to be about 3.6 percent for the high sulfur and 1.8 percent for the low sulfur (achieved by burning gas in combination with coal as a fuel). However, during this test period, the Illinois Power gas meter was functioning improperly and resulted in variable effective sulfur control for the low sulfur fuel.

Results--Table 39 shows the results of measured volume flow data collected at the inlet and outlet of the ESP. As can be seen from the table, the mass flow for the 100 MW tests ranged between 19 x 10^3 to 22.2 x 10^3 lb/min. of stack emission while 60 MW tests ranged from 10.5 x 10^3 to 13.5 x 10^3 lb/min. In general for a given load the coal/gas fuel had a lower total mass emission than the all coal fuel.

Table 40 lists the grain loading and total particle mass rates at the ESP input and output. As would be expected, the inlet grain loading for the coal tests is approximately double that of the coal/gas fuel tests. Tests 9 and 11 are exceptions and are questionable; they will be discussed in the conclusions section. Tests 6 and 11 were found to have contaminated filters and hence were repeated (tests 6R and 11R). The gaseous results collected during tests 6 and 11 were uneffected by the contaminated filters and are presented in this section.

TABLE 39. COMBUSTION GAS FLOW RATES

		INLET TO ESP			OUTLET TO ESP		
TEST #		ACTUAL FLOW CF/Min	STANDARD FLOW DSCF/Min	MASS* FLOW Lbs/Min	ACTUAL FLOW CF/Min	STANDARD FLOW DSCF/Min	MASS** FLOW Lbs/Min
1	1	399,300	261,106	20,984	421,474	270,173	19,993
9	1	353,267	230,635	18,304	339,450	209,927	17,098
11R	1	215,343	133,409	10,536	249,241	150,604	12,011
11	1	248,348	158,838	13,286	246,615	159,152	12,906
12	2	426,630	278,298	22,116	434,405	267,568	21,779
5	2	319,762	203,090	16,544	313,730	195,843	15,963
6R	2	234,636	147,207	11,430	248,323	155323	12,568
6	2	224,977	141,296	11,517	240,860	148,482	11,915
2	3	410,776	241,197	19,649	404,039	239,107	19,546
4	3	284,630	175,350	14,207	285,020	172,039	13,983
10	3	228,751	133,353	10,895	250,376	146,644	12,070
3	4	400,237	235,869	19,186	427,492	250,724	20,558
7	4	311,763	193,781	15,620	314,330	192,380	15,616
8	4	231,831	136,551	11,095	240,851	141,783	11,624

* (1) all coal fuel, no soot blowing, (2) all coal fuel, soot blowing, (3) coal/gas fuel, no soot blowing, (4) coal/gas fuel soot blowing

** Mass Flow includes water vapor

TABLE 40. PARTICLE LOADING MEASUREMENT

			INLET PARTICULATE LOADING			OUTLET PARTICULATE LOADING		
TEST #	DATE	LOAD	STANDARD GR/DSCF	ACTUAL GR/ACF	TOTAL EMITTED Lb/HR	STANDARD GR/DSCF	ACTUAL GR/ACF	TOTAL EMITTED Lb/HR
1	9/13	100 Coal	0.81720	0.53437	1828	0.00421	0.00270	9.75
9	9/15	80 Coal	1.89488	1.23709	3745	0.02777	0.01717	49.46
11R	9/23	60 Coal	0.58979	0.36539	674	0.01155	0.00698	14.90
12	9/12	100 Coal	0.90276	0.58888	2153	0.00810	0.00499	18.56
5	9/17	80 Coal	0.87957	0.55864	1531	0.00384	0.00240	6.45
6R	9/23	60 Coal	1.13817	0.71407	1436	0.00201	0.00126	2.67
2	9/26	100 Coal/ Gas	0.44007	0.25840	910	0.00181	0.00107	3.71
4	9/19	80 Coal/ Gas	0.26700	0.16449	401	0.00224	0.00135	3.31
10	9/24	60 Coal/ Gas	0.35764	0.20849	409	0.00200	0.00117	2.51
3	9/27	100 Coal/ Gas	0.49395	0.29110	998	0.00214	0.00216	4.60
7	9/22	80 Coal/ Gas	0.44195	0.27470	734	0.00248	0.00152	4.10
8	9/24	60 Coal/ Gas	0.43285	0.25495	507	0.00267	0.00157	3.25

Table 41 lists the Orsat analysis and the water vapor concentrations at the ESP inlet and outlet while Tables 42, 43, 44 and 45 list the continuous gas analysis for O_2, CO_2, NO_x and SO_2, respectively. The continuous gas analyses were performed on gas samples extracted from the economizer, ESP inlet, ESP outlet and the stack.

For the most part, all calculations requiring gas concentrations data are done using the continuous data primarily because these data were collected and averaged over the entire test period while the manual data (gaseous) were from grab samples taken at the beginning or end of the test). The continuous data seem more reliable. The data show an average O_2 concentration at the ESP inlet of 4.7 percent and at the outlet of 5.4 percent. This is the predicted direction change since one would expect to have some air leakage into the flue gas. The manual data shows the opposite change (5.3 percent at the inlet and 4.3 percent at the outlet). This type of change would only result if there was sampling error, stratification of gas or rapid oxidation in the ESP. The latter two are highly unlikely in these magnitudes. The Orsat showed ESP inlet and outlet data for CO_2 to be 13.6 percent and 13.9 percent respectively (opposite of the expected change). The continuous analysis indicated an average CO_2 of 14.8 percent at the inlet and 14.7 percent at the outlet (the expected direction of change caused by air leakage). On the basis of this comparison, the continuous gas data seems more realistic and dependable.

TABLE 41. ORSAT ANALYSIS (% Volume)

TEST NO.	DATE	INLET				OUTLET			
		O_2	CO_2	CO	H_2O	O_2	CO_2	CO	H_2O
1	9-13-74	4.9%	15.8	0	7.3	4.6%	15.3	0	8
9	9-15-74	5.8	15.1	0	5.5	4.2	16.7	0	8.9
11R	9-23-74	5.0	13.8	.1	6.3	5.7	12.0	0	9.1
11	9-16-74	6.8	15.4	0	8.5	4.4	18.3	0	6.9
12	9-12-74	5.0	15.5	.3	6.0	4.1	15.5	0	9.7
5	9-17-74	5.2	17.4	0	8.3	5.1	16.9	0	8.6
6R	9-23-74	5.0	13.8	.1	4.7	4.7	12.0	0	8.3
6	9-18-74	6.2	15.4	0	8.6	4.6	17.3	0	9.4
2	9-26-74	4.2	11.8	.1	12.6	4.6	11.9	0	12.9
4	9-19-74	3.8	14.1	0	9.9	3.6	13.5	0	10.8
10	9-24-74	5.7	10.5	0	13.1	4.8	11.2	0	14.1
3	9-27-74	4.7	12.0	.1	12.1	4.5	12.4	.1	12.8
7	9-22-74	5.9	9.7	0	11.3	5.9	10.0	0	12.9
8	9-24-74	5.7	10.5	0	12.0	4.8	11.2	0	13.4

TABLE 42. O_2 CONCENTRATIONS (PERCENT)

TEST NO. \ LOCATION	ECONOMIZER	ESP INLET	ESP OUTLET	STACK
1R	4.2	5.2	5.2	5.9
9	4.9	5.7	5.7	6.5
11	4.3	5.3	5.8	6.6
11R	3.0	4.0	4.9	5.9
12	4.4	5.3	5.3	5.9
5	4.1	5.1	5.3	6.0
6	4.4	5.1	6.0	6.6
6R	3.6	4.4	5.3	6.1
2	3.7	4.8	4.8	5.6
4	4.1	5.2	5.7	6.3
10	4.1	4.8	5.4	6.6
3	3.9	4.9	5.0	5.8
7	4.3	5.3	5.4	6.5
8	3.6	4.1	5.2	5.9

TABLE 43. CO_2 CONCENTRATIONS (PERCENT)

LOCATION TEST NO.	ECONOMIZER	ESP INLET	ESP OUTLET	STACK
1	14.9	14.7	14.7	14.4
9	15.2	14.8	14.7	14.4
11R	15.3	14.7	14.5	14.3
11	16.0	15.6	15.5	15.2
12	17.1	16.8	16.7	16.2
5	15.2	14.8	14.7	14.4
6R	15.3	15.1	14.8	14.4
6	15.2	14.9	14.7	14.4
2	14.7	14.3	14.3	14.0
4	15.5	15.2	15.2	14.4
10	14.6	14.3	13.9	13.7
3	14.1	13.9	14.0	13.5
7	15.3	14.7	14.7	14.1
8	14.1	14.0	13.6	13.2

TABLE 44. NO_x CONCENTRATIONS (PPM)

LOCATION TEST NO.	ECONOMIZER	ESP INLET	ESP OUTLET	STACK
1	261	159	247	248
9	263	268	268	250
11R	337	283	265	243
11	268	268	258	225
12	254	243	242	230
5	262	265	270	246
6R	314	298	283	278
6	218	278	253	264
2	170	191	182	163
4	160	137	125	153
10	123	128	124	105
3	233	213	208	175
7	149	149	140	128
8	120	112	107	95

TABLE 45. SO_2 CONCENTRATIONS (PPM)

TEST NO. \ LOCATION	ECONOMIZER	ESP INLET	ESP OUTLET	STACK
1	2524	2470	2471	2431
9	2794	2734	2711	2615
11R	2734	2634	2528	2400
11	2629	2475	2453	2340
12	2509	2509	2505	2445
5	2652	2610	2562	2454
6R	2613	2538	2400	2340
6	2400	2310	2310	2205
2	1796	1789	1737	1590
4	900	880	825	735
10	1095	1121	1116	1069
3	1345	1350	1373	1305
7	983	963	973	860
8	1175	1225	1152	1090

Table 46 gives the results of the proximate and ultimate coal analyses performed on samples from each test. The results are presented on a dry basis along with the as-received moisture content. The average moisture content of the coal was about 4.3 percent by weight, while the sulfur averaged 3.55 percent by weight as a dry basis or 3.42 percent on an as received basis. The average heat of combustion of the coal is 12,627 Btu/lb on a dry basis.

As described earlier, in order to meet the two sulfur level fuels parameter, a mix between coal and gas was set for the low sulfur fuel tests. The value was to be one half of the high sulfur fuel. A combination of one part coal (measured in Btu) and one equivalent part gas (measured in Btu) would produce an effective sulfur level approximately one half that of the coal. However, an erroneous IP gas flow meter allowed too much gas into the mix during some tests resulting in varying sulfur levels. The corrected coal and gas flows were computed and listed in Table 47 along with the corrected effective sulfur level of the fuel for each test. The data are only presented for those tests which produced acceptable particle data. The average effective sulfur content of the all coal tests was 3.47 percent sulfur as received. The gas feed error was such that it was fairly consistent for a given load, the averages for the 100, 80 and 60 MW low sulfur fuel tests were 1.7 percent, 1.36 percent and 1.43 percent sulfur, respectively.

The ESP efficiency was calculated by the equation:

TABLE 46. COAL ANALYSIS

			DRY BASIS							
TEST	AS RECEIVED MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEAT OF COMBUSTION BTU/LB	CARBON	HYDROGEN	NITROGEN	OXYGEN BY DIFFERENCE
1	4.41	10.27	41.15	48.58	3.38	12,713	69.98	5.14	1.10	10.13
9	4.32	13.66	36.37	49.97	3.60	12,186	67.43	4.88	1.11	9.32
11R	4.56	10.76	41.03	48.21	3.74	12,651	69.11	5.11	1.13	10.15
11	4.44	11.65	39.95	48.40	3.59	12,530	68.25	4.51	1.09	10.91
12	4.65	10.10	40.38	49.52	3.60	12,727	69.60	5.00	1.13	10.57
5	4.31	12.28	39.42	48.30	3.71	12,376	67.56	4.77	1.10	10.58
6R	4.74	10.46	40.85	48.69	3.78	12,659	69.50	5.05	1.10	10.11
6	4.38	10.60	40.97	48.43	3.53	12,697	69.20	5.15	1.14	10.38
2	3.76	10.79	41.0	48.21	3.10	12,565	69.26	5.00	1.11	10.74
4	4.35	10.58	39.59	49.83	3.94	12,711	69.56	5.25	1.13	9.54
10	3.86	9.71	40.87	49.42	3.10	12,773	70.51	4.91	1.18	10.59
3	4.45	9.81	40.95	49.24	3.42	12,780	70.62	5.19	1.15	9.81
7	4.16	10.14	42.10	47.76	3.78	12,769	69.61	5.14	1.15	10.81
8	4.19	10.23	41.16	48.61	3.45	12,646	69.79	5.09	1.14	10.30

TABLE 47. EFFECTIVE SULFUR CONCENTRATION IN THE FUEL

DATE	TEST NO.	LOAD TH	MW ACT	COAL FEED RATE NO/HR	COAL FEED RATE BTU/HRX10^6 (as received)	% SULFUR (as received)	GAS FEED RATE CF/HRX10^3	GAS FEED RATE BTU/HRX10^6 (as received)	FUEL BTU/HRX10^6	EFFECTIVE % SULFUR
9/13/74	1R	100	100+	90,440	1099	3.23			1099	3.23
9/26/74	2	100	100+	44,840	542	2.98	419.6	432	974	1.66
9/27/74	3	100	101+	45,080	551	3.27	406	419	969	1.86
9/19/74	4	80	79+	22,000	267	3.77	443	457	724	1.39
9/17/74	5	80	80–	67,200	796	3.55			796	3.55
9/23/74	6R	60	65	47,920	578	3.59			578	3.59
9/22/74	7	80	79+	22,720	274	3.62	459	473	747	1.33
9/24/74	8	60	60	21,440	258	3.31	330	340	599	1.43
9/15/74	9	80	80–	74,920	874	3.44			874	3.44
9/24/74	10	60	60	21,440	258	3.31	330	340	599	1.43
9/23/74	11R	60	60	47,920	578	3.59			578	3.59
9/12/74	12	100	100	89,400	1085	3.43			1085	3.43
9/18/74	6	60	60+	49,341	599	3.38			599	3.38
9/16/74	11	60	63.5	54,509	653	3.43			653	3.43

1. Percent Sulfur Same From 8 & 10 Assume 8 Write
2. Aver Value for BTU/Hr Test 8 & 10
3. BTU Content of Gas 1030 BTU/LF @60 F

$$\%\text{EFF.} = \frac{\text{(MASS LOADING AT INLET)}-\text{(MASS LOADING AT OUTLET)}}{\text{(MASS LOADING AT INLET)}} \times 100\%$$

The results are presented in Table 48.

Specifications for the ESP design require an output of no more than 0.005 grains/SCF. The ESP met this specification on all tests but 9, 11 and 12. Test log notes indicated the ESP was functioning improperly during test 11 and test 9. During test 9 it was noted that the ESP was noisy, primary voltages and average precipitator currents were fluctuating during the tests and could not be held constant. However, the average precipitation current averaged overall of test 9 (0.51 mA) was comparable to the average for all the other tests (0.52 mA). Test 11 had a much lower average precipitation current, 0.46 mA. This test was also noisy and during the test one stage overloaded and cut off temporarily but was evidently reenergized. Hence, these two tests do not typify normal operating parameters and hence cannot be fit into the test pattern as originally planned.

No explanation for the high outlet loading on test 12 could be determined. Another strange data point was the inlet loading of test 4. It was nearly one half that of the other similar tests. Hence, even though the outlet given loading was 0.0024 g/DSCF (the 4th lowest of 12 tests), the efficiency was the fourth worst of the 12 tests.

As a result of above discussion, data from tests 9 and 11 are considered invalid and are not used to compare the effects

TABLE 48. ELECTROSTATIC PRECIPATOR TEST RESULTS (PARTICLE)

Test No.	Power Plant Load (MW)	Excess Air (% Oxygen)	Fuel Sulfur Content (%)	Soot Blowing	Moisture(2) Content (Vol. %)	Loading (Grains/Dry SCF) Inlet	Outlet	Efficiency (% particulate removal)
1	100	4.2	3.6	No	7.65	0.8172	0.00421	99.46
2	100	4.0	2.31	No	12.75	0.44007	0.00181	99.59
3	100	4.0	1.8	Yes	12.45	0.49395	0.00214	99.57
4	80	4.0	2.31	No	10.35	0.26700(1)	0.00224	99.16
5	80	4.0	3.6	Yes	8.45	0.87957	0.00384	99.56
6	60	4.0	3.6	Yes	6.50	1.13817(1)	0.00201	99.88
7	80	4.0	2.31	Yes	12.1	0.44195(1)	0.00248	99.44
8	60	4.0	2.31	Yes	12.	0.43285(1)	0.00267	99.38
9	80	4.0	3.6	No	7.2	0.89488	0.02777	98.58
10	60	4.0	2.31	No	13.6	0.35764(1)	0.00200	99.44
11	60	4.0	3.6	No	7.7	0.58979(1)	0.0155	98.04
12	100	4.1	3.6	Yes	7.85	0.90276	0.00810	99.12

(1) Samples which deviated from isokinetic condition by more than ± 10%

(2) Average of Inlet and Outlet measurements

of the controled parameters. Test 4 and possibly 12 also have questionable reliability.

Comparison of the efficiency versus load for the valid coal tests (1, 5, 6, and 12), as expected, showed that the efficiency increased with decrease in load (mass flow through the ESP). The coal/gas fuel tests showed an opposite effect. Subsequent discussions in the stratification and non-uniform flow test sections of this report provide possible explanations for this. It should be noted, however, that due to the error in gas flow measurement there was considerable differences in the total ash content of the coal/gas fuel among various loads and, as a result, the comparison of these tests assuming similar fuel type may be invalid.

All comparable pairs of tests (1 and 12, 2 and 3, and 10 and 8) showed a decrease in efficiency with soot blowing of 0.34, 0.02 and 0.06 percent respectively. Exceptions were Tests 4 (questionable) and 7, which showed an increase of 0.28 percent. One would expect soot blowing to have less of an effect on the coal/gas tests (2/3 and 10/8) since there is significantly less loading during these tests. The increase in efficiency with the 80 MW coal/gas tests (4/7), however, is unexplainable and is assumed invalid.

The results (0.34 percent decrease in efficiency with soot blowing) of the coal test seems comparable to the results found during the first ESP tests which found between 0.3 and 0.6 percent decrease in efficiency with soot blowing.

Comparison of efficiency for the two fuels used in the 100 MW test cases indicated a 0.13 percent and 0.45 percent increase with the coal/gas mix fuel with and without soot blowing, respectively. The 80 and 60 MW tests could only be compared for the soot blowing and indicated an opposite response of 0.16 and 0.40, respectively.

Table 49 shows the total particle emission rate and emission per Btu input. For the coal tests, the mass emitted/Btu input decreases with decreasing load quite apparently. For the coal/gas mix, there seems to be a slight increase with decreasing load; however, the differences are very slight compared with coal and are in the area of the detectable limits for the method. The difference in slope of the load vs. mass emitted/BTU between different fuel mixes seems to be more strongly dependent upon the efficiency of the boiler as opposed to ESP performance since the total mass emitted decreases with decreasing load for all valid test conditions and fuels. However, the coal does show a sharper decrease in mass emitted per decrease in load as compared with the coal/gas mixture. The coal test produced 70 to 50 percent decrease in mass emitted per 20 MW change vs. 25 to 10 percent decrease per 20 MW change with the coal/gas mix.

Concentration of O_2, initially (the beginning of each test) set for 4 percent at economizer, averaged 4.04 percent at the economizer, 4.7 percent at the ESP inlet, 5.4 percent at the ESP outlet, and 6.2 percent at the stack. The increase in O_2 concentration of samples further away from the boiler is due to air leakage into the system.

TABLE 49. PARTICLE EMISSION RATE

	Total Mass Emitted (particle)	Total Particles Emitted per Btu Input lb/Btu x 10^6
1R	9.75	0.0088
9	49.46*	0.0565*
11R	14.90*	0.0257*
12	18.56	0.0171
5	6.45	0.0081
6R	2.67	0.0046
2	3.71	0.0038
4	3.31	0.0045
10	2.51	0.0041
3	4.60	0.0047
7	4.10	0.0054
8	3.25	0.0054

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*Invalid Test Points

The O_2 concentration at the economizer average 4.11 percent for the coal tests and 3.95 percent for the coal/gas mix tests. See Table 42 for O_2 concentration for each test.

Concentration of CO_2 (Table 43) as expected decreased in samples taken further from the boiler. The CO_2 concentrations averaged 15.2 percent, 14.8 percent 14.7 percent, and 13.4 percent for the economizer ESP inlet and outlet and stack, respectively. The average CO_2 concentration at the economizer for the coal tests was 15.5 percent and for the coal/gas tests 14.7 percent. This difference is expected since the CO_2 concentration for a given excess air value is lower for gas than coal.

The average NO_x was 228.2 ppm at the economizer, 220.9 ppm at the ESP inlet, 212.3 ppm at the outlet, and 200.2 ppm at the stack. The NO_x concentration showed a marked decrease (43 percent decrease at economizer) with the coal/gas fuel (concentration of 159 percent) as opposed to coal (concentration 280 percent).

A reduction in SO_2 levels was also expected and during the coal/gas tests as opposed to coal tests. The reduction in SO_2 concentration for the coal/gas mixture as compared to the coal was 54 percent at the economizer, the all coal averaged 2,652 ppm SO_2 while the coal/gas average was 1,216 ppm SO_2. The SO_2 concentrations at the economizer, ESP inlet and outlet and the stack was concentrations 2,036 ppm, 1,972 ppm, 1,937 ppm and 1,849 ppm, respectively. (Table 45 gives SO_2 concentrations for each test.)

Table 50 lists the average mass flow rate and mass emitted/BTU input for O_2, CO_2, NO_x and SO_2. The values are averages of the measured mass flows at the inlet and outlet of the ESP.

The mass flow of all gaseous constituents measured decreased with a decrease in load. Soot blowing has no effect on gaseous flow. As expected CO_2, SO_2, and NO_x mass flow emissions are lower on the coal/gas fuel as opposed to the all coal fuel. In general, the unit emissions were predictable on a mass flow basis. A more significant comparison is to relate pounds of a given emission to pounds of input fuel.

Comparison of pounds of NO_x emitted per Btu fuel input to load change with and without soot blowing with all coal fuel indicated that emissions as a function of fuel type seemed to be the highest in the 80 MW area and tend to drop at the 100 MW load and tend to stay even or drop slightly at 60 MW loads. Similar trends are apparent for SO_2 emission per input Btu. However, a more significant drop was noted at the 60 MW level.

Comparisons of tests 6R and 11R (20 percent and 18 percent excess air, respectively) to 6 and 11 (22 percent and 21 percent excess air, respectively) indicate no definite trends in emissions of NO_x and SO_2 as a function of excess air resulting from the magnitude of the fluctuations compared. Comparing test 6R to 6 for a decrease in O_2 (excess air decrease of 2 percent) there is an increase in pounds of NO_x and SO_2 emitted per Btu of fuel. Test 11R and 11 show for a similar

TABLE 50. GAS FLOW RATES

			Mass Flow lb/min				lb Emitted/(Btu Input x 10^6)			
TEST	lb LOAD	CONDITION	O_2	CU_2	NO_x	SO_2	O_2	CU_2	NO_x	SU_2
1	100	Coal	1231	4786	6.2	126	67.23	261.38	0.33	6.88
9	80	No	1119	3982	5.5	115	76.85	273.48	0.37	7.89
11R	60	Soot	563	2845	3.6	71	58.46	295.43	0.37	7.37
11	60	Blowing	787	2706	4.0	77	72.33	248.71	0.36	7.07
12	100	Coal	1289	5603	6.2	132	71.29	309.90	0.34	7.30
5	80	Soot-	925	3606	5.0	100	69.75	271.94	0.37	7.54
6R	60	Blowing	667	2678	4.1	71	69.26	272.89	0.42	7.37
6	60		717	2772	3.6	65	71.84	277.75	0.36	6.51
2	100	Coal/	1028	4209	4.4	86	63.33	259.33	0.27	5.29
4	80	gas no	844	3236	2.2	29	69.98	268.32	0.18	2.40
10	60	Soot	636	2419	1.8	32	63.72	242.38	0.18	3.20
		Blowing								
3	100	Coal/	1073	4160	5.0	67	66.43	257.58	0.30	4.14
7	80	Gas Soot	921	3479	2.7	38	73.97	279.43	0.21	3.05
8	60	Blowing	589	2354	1.5	34	59.01	235.87	0.15	3.40

decrease in O_2 (excess air decrease of 3 percent) there is a decrease in NO_x and SO_2 emission per Btu of fuel.

No reliable information relating to load vs. emissions could be obtained from the coal/gas fuel tests since the coal/gas ratio varied from load to load. The SO_2 emission/Btu input tended to follow the coal/gas ratio more than any other controlled parameters. Table 51 gives the approximate ratios for the coal/gas tests. The 80 MW tests averaged 0.0183 lbs SO_2 per 10^6 Btu input with a 0.58: 1 coal/gas ratio while the highest ratio 1.29:1 coal/gas produced an average 0.0317 lbs/10^6 Btu input. Figure 29 plots these values and shows that the predicted ratio for the 60 MW tests (0.0220 lb $SO_2/10^6$ Btu input) agrees very well with the actual coal/gas ratio. This would imply that the coal/gas ratio is the major controlling factor for the SO_2 pounds of emissions per Btu input and hence, explains the SO_2 variations during the tests with coal/gas mixtures for fuel. However, this is not the case for NO_x or CO_2 as can be seen from similar comparisons.

Comparison of the all coal fuel to the coal/gas fuel on a load to load basis indicate that SO_2 and NO_x emissions are significantly lower per input Btu as opposed to the coal fuel. CO_2 also shows a decrease with the coal/gas fuel. And as expected, water vapor is higher for coal/gas fuel (11.8 percent H_2O) as opposed to coal (7.1 percent H_2O average).

Conclusions--The ESP Design Specifications require the ESP to have an output grain loading of less than or equal to 0.005 gr/SCF.

TABLE 51. COAL TO GAS RATIOS

Test Number	Ratio	Test Number	Ratio
1	1:0	2	1.25:1
9	1:0	4	0.58:1
11R	1:0	10	0.76:1
12	1:0	3	1.32:1
5	1:0	7	0.58:1
6R	1:0	8	0.76:1

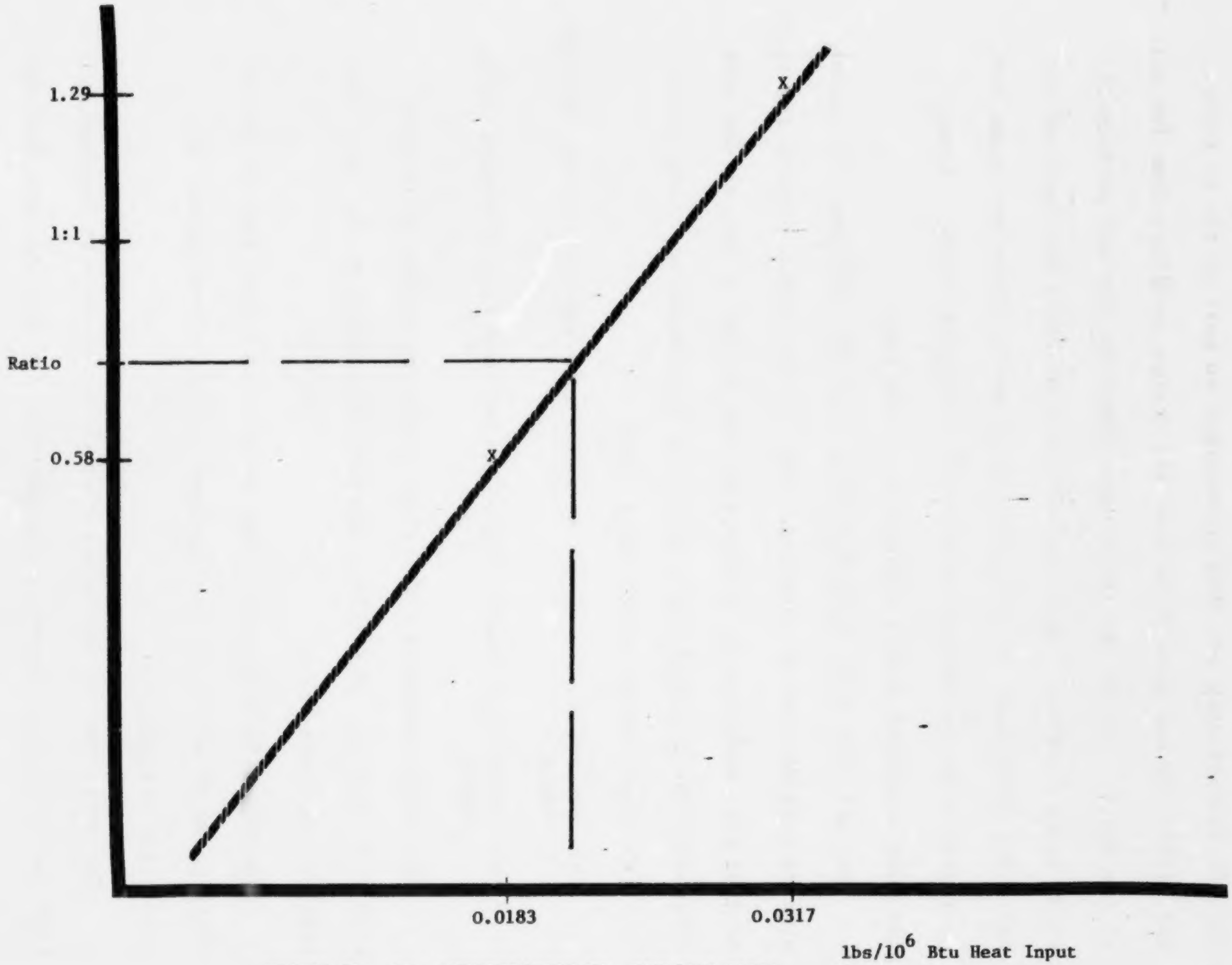

FIGURE 29. NO_x CONCENTRATION VS. COAL/GAS RATIO

The ESP successfully met this requirement on most of the 12 tests. The efficiency was also at or near the design specifications for most of the tests. Two of the three tests where the ESP was performing below specs (loading > 0.005 gr/SCF) were probably the fault of the ESP. The units were exceptionally noisy during these two tests and no reason could be determined for this electrical noise. However, the unit corrected itself shortly after the test.

The all coal fuel tests indicated that ESP efficiency increases with decreasing load as expected. The coal/gas tests produce the opposite effect; however, it is felt that the following factors may have influenced the coal/gas tests to negate any comparison among loads:

(a) Fuel ratios varied among loads

(b) Stratification of gases seemed more apparent during coal/gas tests.

(c) There is a possibility of non-uniform flow affecting these tests.

The tests indicated a decrease in ESP collection efficiency with soot blowing. The effect was more pronounced on the coal tests than the coal/gas tests.

The ESP efficiency was higher with the all coal fuel at 100 MW while at 80 MW and 60 MW the coal/gas mixture showed better ESP collection efficiency.

The total mass of particles emitted decreased with decreasing load for all tests. However, the decrease for the coal/gas fuel was less than for coal.

A comparison of the particle emissions per Btu of fuel input showed that in general there was a decrease in emission per Btu fuel input with decrease in load for the coal tests. The coal/gas fuel test, however, produced the lowest emission/Btu fuel input at 100 MW. The emission level increased at 80 MW and tended to stay the same or drop at 60 MW.

The following observations are outside the original objective of the ESP test. However, they may be of some use in further investigation of coal fired boilers and fuel mixing. The total mass flow of gaseous pollutants increased with increasing load. No discernable pattern of mass flow in SO_2 or NO_x could be determined for small changes (<5 percent) in excess air.

The levels of CO_2, SO_2 and NO_x mass flow decreased significantly with the coal/gas fuel as opposed to the coal fuel.

The mass emissions of NO_x and SO_2 per Btu input of fuel was highest at the 80 MW level and decreased for the 100 MW and 60 MW with coal.

No comparison could be made between load on the coal/gas tests since the coal/gas ratio varied from load to load. It was noted that the SO_2 output/Btu input followed the coal/gas ratio very closely. NO_x output/Btu input did decrease with the addition of gas but it did not follow the ratio as the SO_2 output did.

Overall, the ESP did perform acceptably for the operation of the Cat-Ox unit. The tests, however, did not produce all the expected data relating to the effects of low sulfur fuel, load change and soot blowing for two reasons:

1) Coal/gas mixture is not an adequate replacement for low sulfur coal.

2) Uncontrolled parameters like non-uniform flow, stratification and air leakage were not accounted for in the theoretical prediction.

These parameters will be discussed and investigated in Sections V.

Transient Tests

Objective--The transient test program was a study integrated into the Main Cat-Ox Test Program (Steady State). The object of the transient tests was to determine the impact of transient events on the emissions from a coal-fired boiler with a Cat-Ox FGD system attached to it. The events were categorized by the type of circumstance leading to that particular event. There were three general transient situations identified in the system's operation.

- Planned
- Unexpected/Controlled
- Immediate

The planned event is typified by the scheduled shutdown of the boiler or Cat-Ox system for planned maintenance. For example, the boiler is regularly shutdown once a year for inspection and maintenance. The Cat-Ox system was expected to shutdown approximately every three months for 48 hours or more to allow for cleaning of the catalyst beds. All equipment would be expected to be operating properly and the shutdown would take place in an orderly and controlled fashion. A restart of the boiler and the Cat-Ox system is also defined as a planned and orderly procedure.

The second class of events characterized by some unexpected change in operating parameters or equipment malfunction can have a very broad range of conditions and resultant actions. For example, a serious leak in a boiler tube may necessitate shutdown of the boiler in as rapid a manner as practical. This might allow sufficient time to complete normal shutdown procedures or it might cause the deletion of steps in the procedure because of time constraints. An important characteristic of this class is that the initial event does not immediately cause the boiler or Cat-Ox to shutdown as do events such as the loss of the boiler fire or the disengagement of the Cat-Ox ID fan. Many system malfunctions in this group (unexpected/controlled) may allow long term system operations (hours to days) with little more than a slight loss in system efficiency. Examples of this type might be failure of one coal mill, the failure of a section of the electrostatic precipitator or the development of a void in one of the catalyst beds. In such instances, a controlled shutdown of the Cat-Ox and the boiler could be planned and executed with minimal disruption caused by the initial malfunction. This latter subgroup would strongly resemble a normal or programmed svstem shutdown described in the first group discussed.

The last grouping of events are those that arise primarily through equipment malfunctions or failures and that result in an immediate shutdown (minutes to fractional hours) of either the boiler or the Cat-Ox process. In general these events can result in no stable or long term degraded operating configuration and will necessitate the total system or Cat-Ox shutdown to prevent further damage to equipment and effect necessary repairs. An example of such a failure would be a water wall tube failure which could either extinguish the boiler fire or be severe enough to cause serious disruption of the combustion process. A similar type of situation in the Cat-Ox system would be the loss of acid circulation in the absorption tower.

In addition to the duration of this initial transient, an understanding of the resulting stabilized state operation must be gained in order to determine the impact of the initial event. For instance the fact that the power plant must operate for a period of 48 hours without Cat-Ox SO_2 control during catalyst bed cleaning may be as important as the non-steady state emissions caused by the process shutdown and start-up. No attempt will be made in this study to assess the relative importance. Apart from the initial event that causes a transient operating condition, one must also examine the duration of the transient condition. For purposes of clarification in this discussion, the term "transient" will be defined as the period between the initial event that caused a departure from planned or normal operation and the time the process again reaches a stabilized operating condition. This stabilized condition may be back to normal, degraded in some manner, or result in the shutdown of the process or system.

Schedule--The initial investigation of transient events resulted in the identification of the transient situations listed in Tables 52, 53 and 54. These tables list the event, time required to stabilize and areas of possible impact. Though all these transients could have a possible effect on emissions, only a portion of these events were scheduled for simulation or study. A number of events or situations were excluded from the test program due to the possible consequences (damage or harm to personnel or equipment) of the simulation (generally in the immediate event class) or because simulation of other events would produce a reasonable replication of circumstances caused by the original event. Table 55 lists the schedule tests to be performed that were feasible and acceptable to IPC. The test plan also allowed flexibility to monitor events that occurred during operation that were unexpected or unplanned.

Results--

During the period of time that Cat-Ox was inoperative, a number of unscheduled tests were performed on the boiler alone. The purpose of these tests was to verify that no unexpected emission related changes occurred within the boiler prior to Cat-Ox. It was also felt that a better characterization of boiler transient emission would be valuable in analyzing the effects of similar transients when Cat-Ox was operable.

Unit No. 4 was started from a "cold" condition and brought into operation over an 18 hour period. The lengthy inoperative period

TABLE 52. BOILER TRANSIENTS (ASSUMES NORMAL OPERATION OF CAT-OX)

Transient Malfunction	Result	Time	Emission Characteristics (Concentrations)			Stabilized Operating Modes/Configurations	Emission Characteristics (Concentrations			Operating Tolerances
			SO_2	H_2SO_4	Part		SO_2	H_2SO_4	Part	
Boiler Start-Up	(Cat-Ox off line) Slow increase in heat until min. load condition	Hrs.	↑	↑	↑	Boiler will stabilize at normal load level	N	N	N	Long Term
Boiler Shutdown Programmed	Slow reduction in heat load and pressure. Parts allowed to cool in controlled manner	Min-Hrs	→	→	→	Cat-Ox would be taken off line if possible prior to complete shutdown	—	—	—	Long Term
Load Increase	Coal mill brought on line, burner angle increased	Min-Hrs	↑	↑	↑	Stabilized high load with increased gas flow	N	↑	↑	Long Term
Load Reduction	Coal mill shutdown burner angle lowered	Min-Hrs	↓	?	—	Stabilized lower load with reduced gas flow	N	N	N	Long Term
Coal Mill Failure	Three remaining mills attempt to cover load 85% of Max. Cap.	Hrs-Days	→	→	↓	Reduced load, reduced gas flow	N	N	N	Long Term
Super Heater Tube Reheater Tube	Reduction in capacity Reduction in capacity	Min-Hrs	→	?	↓	Operate until unit can be shutdown for repairs	?	?		Medium Term
Coal Mill Tack Chainbreaks	Three remaining mills pick up immagionary load, fuel gas rich	Min	↑	→	↑	(Burner follows) Home back to normal	N	N	N	—
Blown Boiler Tubes: Wall Tube	Fire lost	Min	↓	→	?	Shutdown	0	0	0	?
ID Boiler Fan	Boiler back pressure	Min	↑	?	?	Boiler would be shut down if problem was not corrected immediately				
Boiler Mouth Bridging	Ash Buildup	Hrs	?	?	↑	Boiler would either cleared or shutdown				
Turbine Mechanical Problems	Dropload, cool boiler and turbine	Min-Hrs	↑	?	↑	Boiler would be shut down if problem was serious				
Boiler Shutdown Emergency		Min	↑	?	?	Cat-ox would be taken off line if possible prior to complete shutdown	—	—	—	Long Term
Fuel Change	Flue gas makeup changes	Hrs	?	?	?	Cat-Ox will remain on line and stabilize at new conditions	?	?	?	Long Term

TABLE 53. PRECIPITATOR TRANSIENTS (ASSUMES NORMAL OPERATION OF CAT-OX)

Transient Malfunction	Result	Time	Emission Characteristics (Concentrations)			Stabilized Operating Modes/Configuration	Emission Characteristics (Concentrations)			Operating Tolerances
			SO_2	H_2SO_4	Part		SO_2	H_2SO_4	Part	
Precipitator Start-Up	Cat-Ox would not be placed back on line until boiler was up to minimal operating level	Hrs	↑	—	↑	Done in connection with a boiler shut-down, Cat-Ox would be taken off line	N	N	N	Long Term Precipitator would stabilize in normal operating conditions
Precipitator Shut-down	Cat-Ox taken off line in normal sequence	Hrs	↑	?	↑	Done in connection with a boiler shut-down, Cat-Ox would be taken off line	— —	— —	— —	
Precipitator Shut-down Emergency	Heavy particulate loading to Cat-Ox, Cat-Ox taken off line as soon as possible	Min	↑	?	↑	Cat-Ox would be taken off line as quickly as possible	↑			Short Term based on particulate emission standards
Short-Out in Precipitator	Stop boiler-Inspect internally for possible cause	Sec-Min	↑	?	↑	Cat-Ox taken off line	↑	?	↑	Short Term based on particulate emission standards
Insufficient Lapping of Collection Plates	Particulate Build-up reduced collection efficiency	Hrs	→	?	↑	Added particulate load to converter bed, early shutdown for cleaning				Long Term (days) if necessary
Over Intense Lapping	Particulate Reentrainment, reduced collection efficiency	Hrs	→	?	↑	Added particulate load to converter bed, early shutdown for cleaning	N	?	↑	Long Term (days) if necessary
Incorrect Precipitator Vibration Time	Reentrainment, reduced collection efficiency	Hrs	→	?	↑	Added particulate load to converter bed, early shutdown for cleaning	N	?	↑	Long Term (days) if necessary
Incorrect Wire Electrode Discharge	Reentrainment, reduced collection efficiency	Hrs	→	?	↑	Added particulate load to converter bed, early shutdown for cleaning	N	?	↑	Long Term (days) if necessary
Clinkers in Precipitator	Stop Boiler-Inspect Internally for possible cause	Sec-Min	↑	?	↑	Cat-Ox taken off line	↑	?	↑	Short Term based on particulate emission standard
High Ash Level in Precipitator Hopper	May short-out controls and form clinkers	Min-Hrs	→	?	↑	If precipitator is shorted out, Cat-Ox will be taken off line	↑	—	↑	Short Term if precipitator is lost based on particulate emission standards
Precipitator Hopper Plugged	May short-out controls and form clinkers	Min-Hrs	→	?	↑	If precipitator is shorted out, Cat-Ox will be taken off line	↑	—	↑	Short Term if precipitator is lost based on particulate emission standards

TABLE 53. (Concluded)

Transient Malfunction	Result	Time	Emission Characteristics (Concentrations)			Stabilized Operating Modes/Configurations	Emission Characteristics (Concentrations)			Operating Tolerances
			SO_2	H_2SO_4	Part		SO_2	H_2SO_4	Part	
Ash Conveyor Plugged	May short-out controls and form clinkers	Min-Hrs	→	↑	↑	If precipitator is shorted out, Cat-Ox will be taken off line	↑	—	↑	Short Term if precipitator is lost based on particulate emission standards
Hopper Vibrator Plugged	May short-out controls and form clinkers	Hrs	→	↑	↑	If precipitator is shorted out, Cat-Ox will be taken off line	↑	—	↑	Short Term if precipitator is lost based on particulate emission standards
Hopper Heater Failure	Condensation, caking of ash, corrosion of hopper steel	Hrs	—	—	—	May cause shutdown to correct service problems	—	—	—	Short Term if precipitator is lost based on particulate emission standards
Failure of ID Fan on Roof of Precipitator	Entrance of fly Ash in top housing of precipitator	Hrs	→	↑	↑	Cat-Ox taken off line if precipitator fails	↑		↑	Short Term if precipitator is lost based on particulate emission standards

TABLE 34. CAT-OX TRANSIENTS

Transient Malfunction	Result	Time	Emission Characteristics (Concentrations)			Stabilized Operating Modes/Configuration	Emission Characteristics (Concentrations)			Operating Tolerances
			SO_2	H_2SO_4	Part		SO_2	H_2SO_4	Part	
Cat-Ox Shutdown Programmed	Normal procedure for catalyst bed cleaning	Hrs	↑	↓	↑	Cat-Ox off line	↑	↑	↑	Long Term
Cat-Ox Start Up	Will be brought on line with boiler operating	Hrs	↓	↑	↓	Cat-Ox operating at boiler load	↓	↑	↓	Long Term
Cat-Ox Shutdown Emergency	(No problem in) Cat-Ox	Min	↓	↑	↓	Cat-Ox off line	↓	↑	↓	Long Term
Acid Pump Failure Temperature or Pressure Changes in Absorbing Tower and Acid Cooling System	Possible line rupture and breakages	Min	→	↑	→	Cat-Ox off line	↑	↓	↑	Long Term
Absorbing Tower and Acid Cooling-High Temp Flue Gas	Temp > 550°F will cause Cat-Ox shutdown	Min	↑	↑	↑	Cat-Ox off line	↑	↓	↑	Long Term
Low Circulating Acid Flow	High Acid Temp <1200 GPM, Cat-Ox must be shutdown	Min	↑	↑	↑	Cat-Ox off line if problem is not corrected quickly	↑	→	↑	Long Term
Low Acid Level in Absorbing Tower	Acid level ≥ 32" can cause Cat-Ox shutdown	Min	→	↑	→	Cat-Ox off line	↑	↓	↑	Long Term
Heat Exchanger Electric Drive Motor Failure	Auxiliary penumatic motor turns heat exchanger at .5 RPM instead of 1.4 RPM shutdown may occur if main motor isn't repaired rapidly	Min	↑	↓	→	Cat-Ox off line if problem is not resolved quickly	↑	↓	↑	Long Term
Re-Heat Burner Failure	Low Flue Gas Temp	Min	↑	↑	↑	Cat-Ox off line if problem is not corrected quickly	↑	→	↑	Long Term
Re-Heat Burner Fuel Change	Temperature transient on change in flue gas make up	Min	?	?	?	Could cause emission to go either way depending on new fuel	?	?	?	Long Term using new fuel
Combustor Control Console Failure	Overheating of ducts and gasses	Min	↑	↓	→	Cat-Ox off line	↑	↓	↑	Long Term
Failure of Combustion Air Blowers	Incomplete conversion of SO_2 SO_3 SO_2 emitted from stack	Min	↑	↓	→	Cat-Ox off line	↑	↓	↑	
Low SO_3 Gas Pressure in Converter	Cat-Ox shutdown if not promptly corrected	Min	→	?	→	Pressure sensor will cause ID fan to trip out to prevent equipment collapse	↑	↓	↑	Long Term
High and Low ΔP in Mist Eliminator	ΔP > 5" H_2O in S.C. or <20" H_2O in H.V. Eliminator would loose efficient process shutdown	Min	→	↑	?	Cat-Ox off line	↑	↓	↑	Long Term
Cat-Ox Pressure Controller Malfunctions	Flue gas leakage metal strain	?	↑	↑	↑	Cat-Ox off line	↑	↓	↑	Long Term
High Flue Gas Pressure in Absorbing Tower	Poor Distribution of liquid and gas flow through packed section	Min	→	↑	↑	Cat-Ox off line	↑	↓	↑	Long Term

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TABLE 54. (Concluded)

Transient Malfunction	Result	Time	Emission Characteristics (Concentrations)			Stabilized Operating Modes/Configuration	Emission Characteristics (Concentrations			Operating Tolerances
			SO_2	H_2SO_4	Part		SO_2	H_2SO_4	Part	
Heat Exchanger Leaks	Incomplete Conversion of $SO_2 \rightarrow SO_3$	Min-Days				Operation with high SO_2 by-pass	↑	→	→	Long Term
By-Passing of Flue Gas Around Seal Edges of Catalyst	High SO_2 by-pass rate and SO_2 emissions to atmosphere	Hrs-Min	↑	→	↑	Cat-Ox must be shut-down to repair this problem	↑	→	→	Long Term
Fouling of Heat Transfer Surfaces on Heat Exchanger	Cat-Ox shutdown while surfaces are cleaned	Hrs-Days	↑	↓	→	Cat-Ox off line if on line cleaners will not remove fouling	↑	↓	→	Long Term
Void Spots in Catalyst Bed	Incomplete conversion of $SO_2 \rightarrow SO_3$. SO_2 values emitted at stack. Catalyst bed cooling to add catalyst may cause shutdown	Days	↑	↓	↑					Long Term
High Temperature of Gas Heat Exchanger Lube Oil	Emergency condition	Min-Hrs	→	→	→	Cat-Ox shutdown if problem is not resolved quickly	↑	↓	↓	Long Term

TABLE 55. TRANSIENT TEST PROGRAM SUMMARY

TEST SUBJECT	Number of Scheduled Tests	Frequency of Natural Occurrence	Expected Parameter Variation	Estimated Duration of Transient	Estimated Duration of Test	Measurement Points Utilized	Comment
BOILER LOAD CHANGE ±	6	Frequent Daily	Up and Down Between 60 and 90 MW	40 Minutes	4 Hours	1 14	
BOILER FUEL CHANGE	3	High Sulfur Coal to Natural Gas					
BOILER SHUTDOWN	1	At least once per year for mainten-ance	Up and Down Between Cold Boiler and 60 MW	4 Hours	8 Hours	1 14	
				8 Hours	10 Hours	1 14	
BOILER START UP	1			8 Hours			
CAT-OX START UP	3	At least 4 times per year for bed cleaning >10/year	Up and Down Between Cold Cat-Ox and operating temperature	8 Hours	10 Hours	1 11,14	
CAT-OX SHUTDOWN	3			1 Hour	4 Hour	1 11, 14	
CAT-OX BURNER FUEL CHANGE	3					1 14	
PARTIAL ESP FAILURE	3		100% to three sections failed	15 Minutes	4 Hours	1 14	Cut 1 Section at a time
CONVERTER TEMPERATURE DECREASE	3		850°F Down to 800°F 1	45 Minutes	6 Hours	1 10, 14	Changed in 10° steps
ABSORPTION TOWER ACID TEMPERATURE CHANGE	3		280°F ± 20°F	30 Minutes Up	8 Hours	1 10, 14	Changed in 5° steps
ABSORPTION TOWER ACID FLOW CHANGE	3		2000 Gallons/minute ±1000 Gallons/minute	30 Minutes Up	6 Hours	1 10, 14	Turn a circulation pump on or off
	1					1 14	
BOILER TUBE FAILURE		6-10/year		Long Term		1 14	
CONVERTER TEMPERATURE INCREASE				30 Minutes		1 10, 14	

NOTE: All Natural Failure Testing to be monitored subject to:
No risk to personnel
No risk to instrumentation and equipment

resulting from a scheduled maintenance (about three weeks) allowed the turbine to cool down to ambient temperature. The difference in the start-up monitored during this test ("cold" start-up) and a start-up that occurs after a short outage resulting from possibly a tube leak is the rate at which the unit is brought on line. When the boiler is in operation for only a few days the turbine remains hot and the unit can be brought into operation at a much greater pace. However, in this particular case the unit must be brought to operating temperature slowly. It took 12 to 13 hours before Unit No. 4 was generating any power and about 13 to 15 hours before coal could be used.

The auxiliary oil burners were lit at about 12:30 a.m., 26 January 1975. It took until 4:00 a.m. for the boiler to build up 50 pounds of pressure at which time the turbine was allowed to turn. At 12:30 p.m. gas became available and replaced the oil. The first coal mill became operational at 2:30 p.m. Approximately 35 MW of power was being generated at 7:10 p.m. when the instruments were shutdown. Table 56 lists plant data over the test period.

Points 1', 3, and 14 had the sampling lines operational. The emissions at these locations were analyzed for SO_2, NO_x, THC, CO_2, O_2 and H_2O. All the data were recorded on strip charts and all but THC and H_2O were recorded on a magnetic tape. Table 57 lists the results taken off the strip charts.

TABLE 56. POWER PLANT RUNNING PARAMETERS, TEST 1

Time	Load MW	Coal Flow Tons/Hr (3)	Gas $10^3 FT^3/Hr$	Air Flow $10^4 CF/Hr$	Steam Flow 10^4 lb/Hr
12 am	0	0	0	15	0
1	↕	↕	↕	17	↕
3	↕	↕	↕	18	↕
4	↕	↕	↕	↕	↕
5	↕	↕	↕	↕	↕
6	↕	↕	↕	↕	↕
7	↕	↕	↕	↕	↕
8	↕	↕	↕	↕	↕
9	↕	↕	↕	↕	↕
10	↕	↕	↕	↕	↕
11	↕	↕	↕	18	0
12 am	↕	↕	0	23	0
1 pm	↕	↕	26	23	0
1:30	↕	↕			
2:00	↕	0	41	25	5
2:30	5			↕	12
3:00	7	6	44[1]	↕	12
3:30	10			25	12
4:00	12	13	31	27	13
4:30	13	14		27	13
5:00	14	15	33	27	15
5:30	14.5	15		34	19
6:00	22	22	33	34	23
6:30	26	22		33	28
7:00	33	27	34	35	29
7:30	40	29		35	31
8:00pm	45	32	32	36	32

(1) Operator stated he had about 50 x 10^3. At this time while computer reads 44 x 10^3.

(2) The Oil Flow Meter is not in operation.

(3) Coal Flow Readings from the Control Room are normally 1.5 times the Coal Flow determined by the Coal Scales.

TABLE 57. EMISSION TEST DATA TTI

Test #TT1 1/26/75

Location: Point 1' (ECON) Description: First Transient Test, Power Plant Start-up Cold Turbine

Time	SO_2 ppm	NO_x ppm	THC ppm	CO_2%	O_2%	H_2O%	
1 am	--	B.D.L.	--	--	--	--	
2 am	60	↑	38	4.0	18.3	--	
3 am			16	4.0	19.3	--	Started Oil Fire 12:30 am
4 am	60		44	5.2	19.5	--	
5 am	↑		22	5.4	20.0	--	
6 am			38	4.4	19.5	2.8	
7 am	↓		42	↑	19.5	3.0	
8 am	60		40		19.5	3.0	
9 am	50		33	↓	20	2.5	
10 am	50		33	4.4	18.0	2.6	
11 am	60		8	4.8	16.0	2.7	Changed to gas 12:30 pm
12 am	90		16	4.8	16.0	2.7	
1 pm	30	↓	46	4.0	16.0	3.5	
2 pm	30	B.D.L.	44	4.0	15.0	3.8	
3 pm	270	180	15[2]	8.0[3]	15.0[4]	4.0	Placed first coal mill in operation 2:30 pm
4 pm	360	220	0	10.4	12.0	4.5	
5 pm	510	190-210	2	10.2	12.5	4.5	
6 pm	900[5]	370-345[1]	2	12.0	10.0	5.0	
7 pm	1050[6]	320-330	4	12.8	8.5	5+	

(1) Possible NO_2 reading of 25 ppm

(2) Peaked to 40 ppm drop to zero

(3) Varied 4 to 10 percent

(4) Varied 17.5 to 13 percent

(5) Peaked to 1590 ppm low of 730 ppm

(6) Peaked to 1260 ppm low of 700 ppm

No significant amounts of SO_2 were noted in either the oil or the gas fuels. Though the SO_2 levels for both cases were near the "noise level" of the instruments the oil showed about twice as much SO_2 as gas (60 ppm and 30 ppm, respectively). Once the boiler was fired on coal, the SO_2 level began to increase steadily, starting at about 30 ppm at 2:30 p.m. to about 1200 ppm and at 7:00 p.m. At this point it was still increasing.

The total hydrocarbon measurements were generally around 35 to 45 ppm for the gas and oil fires. At one point in time (about the time when Illinois Power was changing from oil to gas) THC content of the stack gas exceeded 100 ppm for about a three minute period. Once coal was fired THC content was below 10 ppm. It should be noted that background levels for THC have indicated between 5 and 15 ppm depending on sampling line.

The CO_2 concentrations remained 4 to 5 percent until coal was added at 2:30 p.m. when it began to increase. At 7:00 p.m., CO_2 was 12.8 percent. Similarly, O_2 was steady from 18 to 20 percent until coal burning was initiated. At this time, O_2 concentration began to drop. At 7:00 p.m. it was about 8 percent. Concentrations of these two gases give an indication to the combustion gas flow in the stack as O_2 decreases and CO_2 increases. One can generally assume that the amount of combustion gas in the stack is increasing.

H_2O increased at a fairly steady rate during the test. It started at about 1.5 to 2 percent and at 7:00 p.m. was above 5 percent.

NO_x concentrations were low during the gas and oil stages of start-up. The highest value recorded prior to 2:30 p.m. was 20 ppm which was probably NO_2. However, 20 ppm is well within the noise level of the instruments and may be only noise. Once coal was fired NO_x steadily increased to a high value of 370 ppm at 6:00 p.m. Primarily all the NO_x was NO. The instrument only sensed NO_2 a few times and the highest value was 40 ppm. The increase in NO_x at 2:30 was probably more due to the increased temperature and fuel rate than the addition of coal to the boiler. The gas and oil fires were controlled to maintain a slow constant rise in temperature. However, at 2:30 when the coal was added, the objective was to increase temperature to produce electricity. Hence, the boiler was hotter and more NO_x was produced.

Test 2, as opposed to Test 1, was a start-up from warm condition (the boiler was inoperative for a short period and hence could be brought into operation much faster). The unit was producing power after only 4 hours. The observations were basically the same as the cold start-up but covered a shorter period of time. Table 58 lists the results of this test. Again, SO_2 increased as coal flow increased and NO_2 seemed to increase as temperature increased. Results were similar to the cold start-up tests but the low sulfur coal resulted in lower SO_2 emissions.

Tests 3, 4, 5, and 6 were all load change tests. There was no significant difference among the tests except that test 3 was a

TABLE 58. TEST 2, SEPTEMBER 25. WARM START-UP ON LOW SULFUR COAL

TIME	LOAD MW	COAL FLOW TONS/HR	GAS 10^3 FT^3/HR	AIR FLOW 10^4CF/HR	STEAM FLOW 10^4 LB/HR
8:00 AM	9	0	180	15	30
8:30 AM	10	0	↓	15	30
9:00 AM	12	0	↓	15	30
9:30 AM	25	10 20	↓	24	35
10:00 AM	38	25	180	26	38
10:30 AM	54	0	0		
11:00 AM	74	48	↓	60	58

TIME	SO_2 ppm	NO_2 ppm	CO_2 %	O_2
8:00 AM		BDL	5.6	15
8:30 AM		BDL	5.8	14.7
9:00 AM	690	BDL	9.6	12.5
9:30 AM	690	ADL*	12.8	10.3
10:00 AM	675	↓	13.2	9.3
10:30 AM	780	↓	14.8	8.8
11:00 AM	810			

*About 15 ppm to 30 ppm

high sulfur coal test and 4 was low sulfur coal and tests 5 and 6 were combination coal and gas for at least a portion of the tests. As expected SO_2 increased with increase in coal. No significant changes could be related to the transient nature of the load changes. Tables 59, 60, 61, and 62 present the results of data collected during these tests.

One attempt was made to monitor a Cat-Ox start-up; however, heat exchanger problems caused the start-up to be terminated. No transient tests were performed on Cat-Ox since it did not operated after this point.

Conclusions--The results from the baseline tests produced no surprising information. The boiler showed no significant increase in gaseous emissions caused by transient circumstances.

No actual transient tests were performed on an operable Cat-Ox; however, a theoretical study on the effects of start-ups and load change on Cat-Ox acid strength did indicate that start-ups in particular could cause significant decrease in acid strengths and hence corrosion rates if extra care were not taken to control flue gas flow and temperatures early in the Cat-Ox start-ups. Load changes were easier to control. The detailed study is presented in MITRE document M75-88, "Cat-Ox Product Acid Strength Study," December 1975.

TABLE 59. TEST 3, MARCH 5, 1975. LOAD CHANGE TEST: COAL

TIME	LOAD MW	COAL TON/HR	AIR 10^4 FT^3/HR	STEAM 10^4 FT^3/HR
1:00 PM	101	65	70	70
1:30 PM	92	60	56	56
2:00 PM	70	45	50	45
	↓	↓	↓	↓

TIME	SO_2 ppm	NO_x ppm	CO_2 %	O_2 %	THC ppm
1:00 PM	2280	--	--	--	
1:30 PM	2205	395	14.4	7	BLD
2:00 PM	2190	425	14.4	6.8	BLD

TABLE 60. TEST 4 SEPTEMBER 14, 1976 LOAD CHANGE TEST: COAL

TIME	LOAD MW	COAL TONS/HR	GAS FLOW	AIR FLOW 10^4 FT^3/HR	STEAM FLOW 10^4 FT^3/HR
11:00 AM	40	23		37	25
11:30 AM	40↑	23		37	25
12:00 PM	45	33		55	45
12:30 PM	83	45		65	45
1:00 PM	100	45	some gas to make 100 MW	65	45

TIME	SO_2 ppm	CO_2 %	O_2 %
11:00 AM	660	13.2	11
11:30 AM	690	14.4	8.8
12:00 PM	1020	15.4	6.3
12:30 PM	1020	15.2	6.0

TABLE 61. TEST 5 SEPTEMBER 15, 1976 LOAD CHANGE TEST: COAL/GAS MIX

TIME	LOAD MW	COAL TONS/HR	GAS	STEAM $10^4 FT^3/HR$	AIR $10^4 FT^3/HR$
8:45 AM	50	45	0	58	54
9:00 AM	78	50	0	60	62
9:30 AM	85	47	started to add 140	60	62
10:00 AM	85	48	140	60	62

TIME	SO_2 ppm	CO_2 %	O_2 %
8:45 AM	990	14.4	5.8
9:00 AM	1000	14.6	6.2
9:30 AM	1005	14.8	6.2
10:00 AM	990	--	--

TABLE 62. TEST 6 SEPTEMBER 17, 1976 LOAD CHANGE TEST: COAL/GAS MIX

TIME	LOAD MW	COAL FLOW TONS/HR	GAS FLOW 10^3 FT^3/HR	AIR FLOW 10^4 FT^3/HR	STEAM FLOW 10^4 FT^3/HR
8:00 AM	25	35		35	20
8:30 AM	45	40		55	42
9:00 AM	82	50	80	68	65
9:30 AM	100	57	150	70	68
10:00 AM	100	57			

TIME	SO_2 ppm	CO_2 %	O_2 %	Comment
8:00 - 8:30 AM	712	14	9.5	
8:30 - 9:00 AM	720	15	7.0	
9:00 - 9:15 AM	780	15.4	6.0	
9:15 - 9:30 AM	735	15.4	6.0	gas increased here
9:30 - 10:00 AM	705			

Special Tests

Ancillary Test Block--During the period of time that Cat-Ox was inoperable, discussions with EPA determined a list of six areas that might be investigated if time and equipment were available. The scope of these tasks were limited by the funds already allotted for Cat-Ox and the use of equipment currently available. The six items were:

- Examine the effects of low sulfur coal on the ESP at IPC unit 4 boiler (low resistivity ash)
- Examine the effect of gas flow rate flow rate on ESP efficiency
- Evaluate NO_x formation in the ESP
- Investigate gas stratification
- Perform material balances on SO_2, SO_3, sulfate and trace metals
- Determine any correlation between particle size and trace metal content of fly ash.

Test plans or at least preliminary baseline type test plans to determine if the desired objective could be obtained within the scope of the project were completed. Some testing on data collection efforts were performed at least in a preliminary mode for most of the tasks.

Schedule/Test Plan and Results

Low Sulfur Fuel Tests--The effects of low sulfur coal on ESP performance was investigated and compared with the ESP performance for the normal high (3.6 percent sulfur) sulfur coal. The comparison between ESP performance for each of the fuels was made on a mass of particulate matter emitted/Btu fuel input basis instead of ESP efficiency.

The tests were compared in this manner for two reasons. First, comparison in this way will relate directly to the environmental standards set out for particle removal efficiency while ESP efficiency does not necessarily directly relate to emission levels, but only to ratio of removal of particles in versus particles emitted. Also, the constraints of the tasks required use of only available equipment, and only one particle sampling train was available (two are required for ESP efficiency determination).

The tests were run according to EPA Method 5 as outlined in the Federal Register New Source Standards, 23 December 1971. The train was modified with an instack filter because a heated probe of sufficient length was not available.

A series of three tests was run with a specific low sulfur coal after allowing more than 24 hours of soak time and the tests were spaced at least 24 hours apart. Unit 4 was then to switch to high sulfur coal and a series of four tests under similar circumstances were run. All samples were taken at point 14 at mid-point of the Unit 4 stack.

Two other groups of similar tests were discussed with IP and planned; however, the required equipment (EPA Sampling Train) became unavailable prior to the scheduled tests.

The effect of low sulfur coal fly ash on the ESP can vary with the type of coal. The low sulfur coal tested during the Electrostatic Precipitator Tests (MITRE Report M75-51) surprisingly caused no degradation to the efficiency of the precipitator over the test duration. Since low sulfur coal is not used in Unit 4 regularly, there have been no other attempts to verify or explain these results. It is believed the low-sulfur test and conditioning durations in the subject report may have been too brief.

During the first week in December 1975, Illinois Power Company used low sulfur coal purchased from the "Blue Diamond Coal Company" in the No. 4 boiler.

The proximate and ultimate analysis is shown in Table 63. Sample 1 was extracted from a train of 19 cars and Sample 2 from a train of 22 cars. Both trains were supposed to have come from the same Starfire mine, however, the analysis of the coals indicated to Illinois Power that each train was from a separate Blue Diamond Mine. The first being from the Starfire Mine and the second from the Leatherwood Mine.

A total of seven tests were run by MITRE--three on low sulfur and four with the Illinois #6 seam high sulfur coal normally used by Wood River. The results and data are presented in Table 64.

The low sulfur coal was in use for about two days prior to testing in order to condition the flue gas path. The first test

TABLE 63. LOW SULFUR COAL ANALYSIS

PROXIMATE	SAMPLE 1 As Received	(train 1) Dry	SAMPLE 2 As Received	(train 2) Day
% Moisture	2.70	—	5.28	—
% Volatile Matter	34.64	35.60	33.63	35.50
% Fixed Carbon	54.10	55.60	49.69	52.46
% Ash	8.56	8.80	11.40	12.04
% Sulfur	0.97	1.00	1.00	1.06
B.T.U.	13057	13420	12190	12870
ULTIMATE				
% Carbon	72.54	76.41	69.32	73.39
% Hydrogen	5.36	5.65	4.62	4.90
% Oxygen, by difference	7.10	7.49	6.43	6.81
% Nitrogen	1.74	1.83	1.43	1.51
% Ash	6.96	7.33	11.64	12.32
% Sulfur	1.10	1.16	0.80	0.85
% Chlorine	0.13	0.13	0.21	0.22
% Moisture	5.07	--	5.55	--
Mine =	Starfire		Leatherwood	

TABLE 64. TEST RESULTS AT POINT 14

			FEED RATES			STACK GAS	
TEST NO.	DATE	LOAD MW GROSS	COAL TPH	AIR $\times 10^4$ LB/hr	STEAM RATE $\times 10^4$ LB/hr	MASS LOADING gr/scf	MOISTURE % BY VOLUME
LS1	12/3/75	100	52	66	66	.00985	7.9
LS2	12/4/75	100	57	66	66	.0135	8.6
LS3	12/5/75	95	45	63	63	.0787	7.6
HS1	12/9/75	102	60	70	70	.0295	12.2
HS2	12/12/75	82	50	57	57	.0094	14.0
HS3	1/12/76	99	53	70	69	.0094	12.6
HS4	1/14/76	102	45	70	70	.0111	11.4

indicated a level of plant emissions equivalent to those experienced with standard operation and the normal high sulfur coal. However, the second test showed a significant increase in emissions as well as poor ESP electrical operation* (Table 65), a number of stages were noisy (electrically) and serious static charge was noted in the stack gas and on the probe. All conditions worsened on the third low sulfur test--output grain loading increased almost 600 percent; all but one of the ESP stages were noisy and some would reach overload voltage and temporarily shut off. The static charge in the stack gas and on the probe was very apparent. The sampling probe had to be grounded to keep the operators from being shocked. The high secondary voltage low secondary current condition is typical of back corona conditions caused by resistive fly ash. The reentrainment of charged ash by sparking could have caused the probe charge observation. Following the low-sulfur test shown, approximately two days' soak time was given to the unit when it was returned to high sulfur coal, which may have been insufficient. The first test indicated abnormally high emission for this particular coal; however, all later tests indicated normal operation was restored.

During the first and second low sulfur tests, independent tests were run in parallel with MITRE's (through IP). These tests were performed at the output of the ESP (Pt3) and produced results

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*Secondary kV readings not available.

TABLE 65. ESP ELECTRICAL DATA

TRISET #	1	2	3	4	5	6	7	8
TEST #	PRIMARY VOLTAGE							
LS1	380	390	$325^{\pm 40}$	$320^{\pm 15}$	$280^{\pm 15}$	Off Scale Low	310^{+10}	270
LS2	300±40	370±10	290±15	290±10	240±20	---	320±30	290
LS3	280±10	330±20	260±10	290±10	280±20	---	330±10	300
HS1	360	330	380	340	360	---	320	280
HS2	320	280	340	340	340	360	280	270
HS3	350	310	380	340	380	320	300	240
HS4	360	310	380	340	360	320	300	250
	E. S. P. AVG. SECONDARY CURRENT (MA)							
LS1	0.40	0.65	0.3±0.05	0.41±0.01	0.19±0.01	0.3	0.12	0.6
LS2	0.25±0.03	0.61±0.01	0.3±0.02	0.5±0.01	0.18±0.01	0.3	0.14±0.01	0.6
LS3	0.28±0.1	0.35±0.5	0.26±0.1	0.40±0.2	0.18	0.29	0.14	0.6
HS1	0.42	0.45	0.46	0.32	0.27	0.29	0.15	0.6
HS2	0.4	0.42	0.45	0.44	0.26	0.25	0.15	0.56
HS3	0.41	0.44	0.45	0.30	0.28	0.18	0.17	0.57
HS4	0.42	0.44	0.4	0.28	0.27	0.18	0.15	0.56
	E. S. P. PRIMARY CURRENT (Amps)							
LS1	75	90	60±10	80±5	40	50	80	95
LS2	50±10	85±2	65±5	90±5	25±5	50	75±5	95
LS3	60±5	60±5	60±5	90±10	40±5	50	75±5	95
HS1	75	70	80	65	55	50	85	95
HS2	75	70	80	85	52	55	85	95
HS3	75	60	80	60	55	40	85	95
HS4	75	70	70	60	55	40	80	95

similar to MITRE's results. The first day's tests averaged around 0.005 gr/DSCF, and the second day's was slightly above 0.01 gr/DSCF. No IP sponsored tests were run after this date (See Table 66).

H_2O data in Table 66 do not agree with MITRE values. The Orsat O_2 values appear to be in error. The test 1 outlet grain loading (ASME) is substantially lower than MITRE's (method 5). The test 3 values are in agreement, however.

These baseline tests suggested a number of implications regarding Cat-Ox process operation with low-sulfur coal. First, the low sulfur coal (at least this type) did degrade ESP performance as is typically found in other power stations. The increasing grain loading with usage implies more than five days of soaking is required to reach stable operating conditions. There is a strong possibility that insufficient soak time is the reason no difference in emissions between low sulfur and high sulfur coal was measured during the ESP baseline tests (EPA Report 600/2-75-037). Much more testing is required to determine any quantitative effects of low sulfur coal on ESP performance, since there were not enough data collected to determine if the output emissions had leveled off by the third low sulfur test (fifth day) or were still changing. A possibility also exists that the large decrease in efficiency could be related to the second type of low sulfur coal used rather than the first type.

It does seem necessary that the ESP be at least tuned specifically for the low sulfur coal to be used if it is to be in operation

TABLE 66. DATA FROM IPC SUBCONTRACTOR TESTS

Date	12-3	12-3	12-4
Inlet to ESP			
Mositure %	5.9	6.2	6.4
DSCF/Min	340,500	340,500	316,100
Loading gr/DSCF	0.4938	0.6646	0.8149
Outlet from ESP			
Moisture	5.8	5.0	5.7
DSCF/Min	314,200	336,500	292,900
Loading (gr/DSCF)	0.0056	0.0051	0.0139
% Removal	98.86	99.23	98.29
Panel Readings			
Gross Power	97 MW (computer printout)		97.6 MW
Air M lb/hr	650		655
Steam M lb/hr	660		673
O_2 %	3.8 (economizer)		3.9
O_2	7.5	8.9	13.0
CO_2	13.5	11.8	6.5
(Dry basis)			

for any extended length of time. Tuning effort would jointly involve IPC and the ESP manufacturer's personnel. More comprehensive testing would be desirable to quantify the effects of low sulfur coal on efficiency.

This low sulfur test series was run on a low level of effort due to the limited equipment and number of personnel on site. Only particles and volume flow were measured since the gas measurement equipment was not in operation and the manpower was not available to operate it.

IPC is currently using another type of low sulfur coal which does not seem to have the drastic effect on the ESP as the low sulfur coal that was employed for these tests. However, due to equipment and time restraints no quantitative results could be determined for this coal.

Flow Rates vs. ESP Efficiency--The primary concern of this task was to investigate the effects of nonuniform* flow across the ESP with respect to removal efficiency. Interest in this problem arose after the results of the "Test Evaluation of Cat-Ox High Efficiency Electrostatic Precipitator" (EPA Report 600/2-75-037) indicated that the measured removal efficiencies did not agree with predicted theoretical efficiencies.

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*In this instance the term nonuniform implies varying flow over individual sides of the ESP and does not mean or consider effects inside the ESP.

It was assumed during the tests and in the theoretical calculations that flow in volume/sec./area cross section was uniform throughout the ESP. There are other parameters which were assumed constant and may have also contributed to the discrepancies between measured and theoretical efficiencies; however, nonuniform flow at one or more of the load levels was a prominent problem. Some evidence of nonuniform flow was noted as far back as the 24 hour acceptance tests. The configuration of the ID fans and ESP for unit 4 are conceptually shown in Figure 30. Each fan is controlled independently and there is no automatic means to assure equal flow through each fan. A short time after the ESP tests, described in M75-51, Illinois Power found the fans (RPM and amperage) out of balance and balanced them. After that, however, preliminary checks performed while setting up the DP transmitters in the MITRE measurement system indicated large draft difference existed (static pressure $^+$1.0 Vs $^+$0.4 in. H_2O) between the two sides of the input duct to the ESP, which may imply different flow rates.

The effects of nonuniform flow on efficiency can be theoretically predicted using the formula

$$\eta = 1 - e^{-\left(W \cdot \frac{A}{F}\right)}$$

Where

η = fractional efficiency of ESP

W = rate constant or drift velocity in ESP

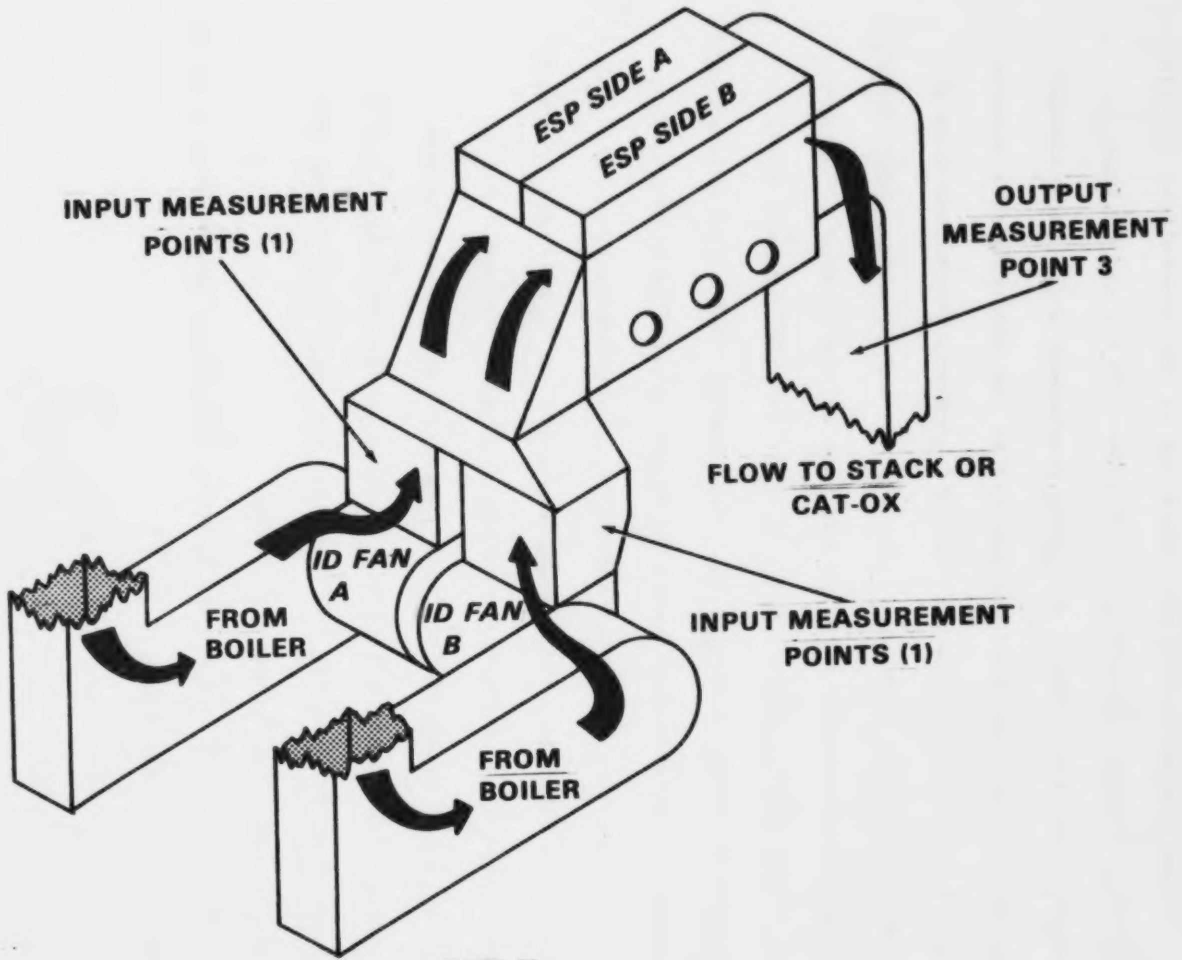
ESP SIDE A
ESP SIDE B
INPUT MEASUREMENT POINTS (1)
OUTPUT MEASUREMENT POINT 3
FLOW TO STACK OR CAT-OX
ID FAN A
ID FAN B
FROM BOILER
INPUT MEASUREMENT POINTS (1)
FROM BOILER

FIGURE 30

CONCEPTUAL VIEW OF FANS AND ESP

A = Plate Area

F = Volume Flow

W,A,F are dimensionally consistent units

Now assuming the following:

$$W.A = 1.174 \times 10^6 \text{ ft}^3/\text{min for each ESP side}$$

$$F = (\text{Total } 410{,}900 \text{ ft}^3/\text{min or if uniform } 205{,}450 \text{ ft}^3/\text{min}$$

Then the efficiency* assuming uniform flow would be equal for both sides of the ESP and is given by:

$$\eta = 1 - e^{-1.174 \times 10^6/205{,}450} = 1 - e^{-5.714}$$

$$\eta = 1 - 0.0033 = 99.67\%$$

Assuming an input grain loading of 1.5 gr/SCF (higher than normal) the output of the ESP would be:

$$1.5\text{g/SCF} - (1.5 \times .9967) = 0.005 \text{ gr/SCF}$$

the outlet stopper in this unit is 0.005 gr/SCF so the guaranteed removal would in this case be 99.67 percent.

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*From "Pollution Engineering Manual," U.S. Department of Health, Education and Welfare.

If the same total flow, grain loading, plate area and drift velocity are used the effect of nonuniform flow can be predicted if we assume 40 percent of the total flow (164,360 CFM) is through Fan A and therefore Side A of the ESP while 60 percent of flow is through Side B (246,540 CFM); then efficiency across side A is:

$$\eta = 1\text{-}e^{-1.174 \times 10^6/164360}$$

$$\eta = 1\text{-}.0008 = 99.92\%$$

Hence Side A emits:

$$1.5 - (1.5 \times .9992) = 0.0012 \text{ gr/SCF}$$

For Side B:

$$\eta = 1\text{-}e^{(-1.174/246540) \times 10^6} = 99.25\%$$

Hence B emits 1.5 - (1.5 x .9915) gr/SCF = 0.0128 gr/SCF

Then for non-uniform flow (40 percent A-60 percent B)

The total particulate matter emitted (M_e) is:

$$M_e = (.4 \times .0012 \text{ gr/SCF}) + (.6 \times .0128 \text{ gr/SCF})$$

$$= .0048 + .0077 = .0125 \text{ gr/SCF}$$

This is an increase over uniform flow of 2.5 times.

It should be noted that for these calculations the precipitator rate parameter W was assumed a constant when in actuality it is also a function of velocity due to the wide range of particle sizes. Hence the rate parameter can also be affected by nonuniform flow. The actual effect would have to be determined experimentally since sufficient data are not available to calculate it.

Considering this theoretical argument as well as the unresolved ESP test data and experience indicating that the Cat-Ox ESP does at times run under nonuniform conditions, a number of exploratory tests were planned in order to develop baseline information on nonuniform flow.

All initial tests were to be run at about 80 MW. This would have allowed the unit a wider latitude of imbalance since the ID fans would not have operated at full load. The volume flow across Sides A & B were to be set uniform for at least the first and last two tests and set at three different nonuniform settings for a series of six tests in between.* Table 67 shows some possible settings for the flow ratios during a test sequence. The flows would be set by measuring velocity over each side of the ESP inlet prior to a test. Attempts were to be made to keep the excess air settings and coal type the same for all tests. Tests at other loads would be scheduled as required. The settings were hypothetical and were never finalized with IP since EPA sampling equipment was unavailable at the planned test periods and time and manpower availability were limited after that time frame.

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*Due to normal variations in flow overtime at a power plant the test period should be kept as short as possible, i.e., 2 to 3 hours.

TABLE 67. Test Flow Ration for ESP

TEST#	FLOW SETTING	
	A	B
1	50%	50%
2	50%	50%
3	70%	30%
4	70%	30%
5	30%	70%
6	30%	70%
7	40%	60%
8	40%	60%
9	50%	50%
10	50%	50%

Though no specific testing could be accomplished with respect to nonuniform flow, some older test data (from the ESP tests) were sufficiently complete to make some preliminary comparisons and observations as to the effects of nonuniform flow.

The flow conditions were recorded for two tests:

Test A 9/13/74 100 MW Load
Ill. High sulfur fuel No Soot Blowing
Inlet - 0.81720 gr/SCF Outlet - 0.00421 gr/SCF

Test B 100 MW
Ill. High sulfur fuel No Soot Blowing
Inlet - 0.90276 Outlet - 0.00810

Since the flow over each side of the ESP on test A differs by less than 1 percent, test A is used in the Duestch equation to empirically determine the precipitation velocity parameter.

Test A

$$\eta = .9946 = 1-e^{-x/197999.8}$$

$$X = 1033816.4$$

Then using this parameter in the test B case we see that if flow were uniform across the ESP

$$\eta = 1-e^{-\frac{1033816.4}{213902.5}} = 1-e^{-4.833}$$

$$\bar{\eta} = 99.21 \text{ percent}$$

the measured efficiency was 99.12 percent, slightly lower.

Further investigation into the data indicated that the flow was not uniform going into each side of the ESP. Side A showed a flow of

2.214×10^5 CFM indicating about 54 percent of the flow was in side A and 46 percent in side B. If we apply this to the Deutsch equation as in the example, the efficiencies for each side were:

$$A = 1-e^{-4.669} = 99.06\%$$

$$B = 1-e^{-5.008} = 99.33\%$$

This implies the outlet grain loading of side A is theoretically 0.00849 gr/ft^3 and side B is 0.00605 gr/ft^3 the average loading for the ESP would be 0.0074 gr/ft^3 which gives an efficiency of 99.18 percent which is fairly close to the measured result.

The indication from these calculations is that the nonuniform flow effect is not large enough to cause the problems or disagreements experienced in the ESP tests discussed earlier. However, there may be a combined effect which includes nonuniform flow and other parameter variations which may decrease efficiency. In any case, the effect of differing flow rates into each side of the ESP has the potential to have drastic effects on ESP efficiency and for any comprehensive test program should be planned to prevent or measure and compensate for this problem.

NO_x Formation in the ESP--The formation of ozone (O_3) in an ESP due to corona discharge and its activity in the ESP was investigated as part of this task. It was felt that generated O_3 might react to form

NO. There was no available method to determine ozone concentrations in the ESP and the parameters to make theoretical estimates were not accessible, hence the task was investigated solely by looking for the possible second order effects of ozone (i.e., increase in NO_2 concentration due to O_3). Ozone concentrations, however, were expected to be very low if present due to the low spark rate of this ESP. Reactions from O_3 should produce a different ratio in $NO:NO_2$ and $SO_2:SO_3$ between the inlet and the outlet of the ESP, since it is unlikely that O_3 will remain stable and untreated for any length of time in this atmosphere.

A number of tests* were run monitoring the ESP for NO_2 and NO_x at the inlet and the outlet the NO_x values ranged from about 430 ppm to 490 ppm but showed no statistical evidence of change between the inlet or outlet that was greater than the standard deviation or that was not the result of other causes (system leakage). The NO_2 data were just within the detectable range for the calibration and settings of the instrument. However, no pattern could be determined that indicated any increase on the outlet side of the ESP. A second series of tests were run monitoring NO_2 only (this allowed the instrument to be calibrated such that its sensitivity was greater). The results were similar in that no significant increase (>8 ppm) was detected in between the inlet and outlet measurements.

Similar investigations into SO_2/SO_3 concentrations produced no evidence that ozone was causing an increase in SO_3.

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*All tests were run when the ESP was at positive pressure.

A few samples of fly ash were collected and analyzed to determine if some of the products could be occluded on the surface of the fly ash. No significant results were obtained.

The problem of measuring ozone formation and its fate in an operational ESP was found to be beyond the capabilities of the equipment available at the Cat-Ox site. Factors such as the low level of ozone generation and its uncertain fate, combined with possible system leakage, and power plant variationm, made it difficult to make any determination without a full scale test program.

Any future investigations into these effects should include an ozone measurement as well as a more sensitive NO_x measurement system The regional ESP parameter to theoretically determine ozone formation should also be available and the parameters controlled.

Gas Stratification--The phenomenon of gas stratification has been known to occur in boilers for some time. The primary objective of the stratification study was to determine if the phenomenon did exist at this facility and what effect it might have on ESP performance.

The first series of tests run investigating stratification was performed at the air heater. Results of a typical test are presented in Tables 68 and 69. Each point was sampled for about 5 minutes. The tests quite readily showed the presence of stratification due to air leakage. This condition (caused by flue gas dilution with air) can be identified when analysis from point to

TABLE 68. GAS TRAVERSE OF NOVEMBER 15, 1971
100 MW, B FUEL, NO SOOT BLOWING, NORMAL EXCESS AIR
NORMAL BURNER ANGLE, LOCATION 2

PORT	POINT	SO_2	O_2	PORT	POINT	SO_2	O_2
4 STRAIGHT	1	1530 PPM	7.3%	1 SIDE	1	1710 PPM	5.8%
	2	1620 PPM	7.1%		2	1800 PPM	5.2%
	3	1620 PPM	7.1%		3	1905 PPM	4.3%
	4	1590 PPM	7.5%		4	1920 PPM	4.0%
	5	1575 PPM	7.6%		5	1983 PPM	3.5%
	6	1635 PPM	7.0%		6	1920 PPM	4.1%
	7	1680 PPM	6.7%		7	1950 PPM	3.8%
	8	1785 PPM	5.8%		8	1890 PPM	4.4%
	9	1836 PPM	5.4%		9	1965 PPM	3.6%
	10	1770 PPM	6.2%		10	1830 PPM	4.8%
4 SIDE	1	1710 PPM	6.4%	1 STRAIGHT	1	1680 PPM	6.0%
	2	1836 PPM	5.2%		2	1797 PPM	5.1%
	3	1837 PPM	5.1%		3	1848 PPM	4.6%
	4	1800 PPM	5.5%		4	1755 PPM	5.5%
	5	1890 PPM	4.7%		5	1764 PPM	5.5%
	6	1890 PPM	4.9%		6	1770 PPM	5.3%
	7	1950 PPM	4.2%		7	1896 PPM	4.1%
	8	1860 PPM	5.0%		8	1845 PPM	4.7%
	9	1950 PPM	4.3%		9	1845 PPM	4.5%
	10	1860 PPM	5.0%		10	1830 PPM	5.0%

TABLE 69. GAS TRAVERSE OF DECEMBER 2, 1971
50 MW, A FUEL, NO SOOT BLOWING, MAXIMUM AIR EXCESS,
NORMAL BURNER ANGLE, LOCATION 2

PORT	POINT	SO_2	O_2	PORT	POINT	SO_2	O_2
4 STRAIGHT	1	1452 PPM	9.9%	1 SIDE	1	1767 PPM	7.5%
	2	1470 PPM	9.8%		2	1743 PPM	6.5%
	3	1650 PPM	8.6%		3	1845 PPM	6.2%
	4	1650 PPM	8.5%		4	2025 PPM	6.7%
	5	1737 PPM	7.8%		5	2004 PPM	7.5%
	6	1818 PPM	7.4%		6	1950 PPM	6.5%
	7	1836 PPM	6.8%		7	2004 PPM	5.8%
	8	1830 PPM	7.6%		8	1980 PPM	6.2%
	9	1866 PPM	7.2%		9	1968 PPM	6.1%
	10	1773 PPM	7.8%		10	1959 PPM	6.0%
4 SIDE	1	1659 PPM	8.4%	1 STRAIGHT	1	1740 PPM	7.3%
	2	1680 PPM	8.4%		2	1905 PPM	7.8%
	3	1818 PPM	7.4%		3	1950 PPM	7.0%
	4	2010 PPM	6.2%		4	1896 PPM	5.5%
	5	1980 PPM	6.3%		5	1785 PPM	5.7%
	6	2067 PPM	5.9%		6	1917 PPM	6.2%
	7	1950 PPM	6.6%		7	2013 PPM	5.9%
	8	2037 PPM	6.0%		8	1965 PPM	6.0%
	9	1833 PPM	7.4%		9	1980 PPM	6.1%
	10	1818 PPM	7.4%		10	1998 PPM	6.2%

point show SO_2 and O_2 changes occurring in opposite directions. Though the boiler conditions do fluctuate while operating parameters are unchanged the magnitude of the variations are not of the order found here, i.e., point 1 side 1 was 5.8 percent O_2 while point was 3.6 percent O_2. Normal changes are less than ±1 percent O_2.

Differences in gas concentrations caused by stratification of gas due to poor mixing was not as apparent. Some areas where SO_2 and O_2 changes did not fit the patterned change (opposite direction to each other) such as Table 68; side position 4, 5 to 6; "straight" position 1, 8 to 9, 9 to 10 and 4 to 5 showed some discrepancy. However, the variations were too limited to draw any final conclusions from this test series.

The main observations were that sampling times for each point should be longer and test times shorter to reduce the effects of normal boiler fluctuations.

This series of tests was run at the economizer. The purpose was to make a determination of stratification in the economizer but not necessarily quantify it. Analysis of the preceding tests indicated that it would be possible to determine the presence of stratification in the economizer by a simple traverse across the economizer. This would reduce the effect of fluctuating boiler conditions with time by:

- reducing the total test time
- making it possible to increase sampling time to greater than the 5-7 minute period determined in the previous tests.

The actual sampling time was 10-15 minutes per point. A second sampling probe was continuously in operation at location 4. The data collected by it were used to assure that there was no significant changes in the average boiler condition. The sample was monitored for SO_2 and O_2.

The actual stratification measurements were made at 8 points across the economizer. The data collected at each point for CO_2, O_2 and SO_2 were averaged and listed in Table 70.

The table shows some significant differences in the constant concentrations from point to point. Some, like point 1 (high O_2 low SO_2 and CO_2) can be explained by air leakage into the economizer. However, other differences such as between points 4 and 5 where SO_2 and O_2 decrease from 4 to 5 for all tests while CO_2 stays relatively constant (except for test 3) indicate the presence of stratification. Other changes (such as between point 2 and point 3 on tests 2 and 4 where SO_2 is constant and O_2 increases considerably) can only be explained by stratification.

Though similar trends were seen in all tests between points 4 and 5 in general the stratification is variable from test to test. This might indicate that the stratification is dependent on burner characteristics, fuel variables, fuel flow rate, and fuel air ratio at the burner area.

This idea is further supported by experiences during coal/gas fuel tests. It was observed (though not recorded) that there were

TABLE 70. STRATIFICATION AT ECONOMIZER

SAMPLING POINT	TEST 1			TEST 2			TEST 3			TEST 4		
	SO_2	O_2	CO_2	SO_2	O_2	CO_2	SO_2	O_2	CO_2	SO_2	O_2	CO_2
1	1980	7.5	13.5	2100	7.1	13.6	2445	5.5	14.5	2430	6.6	14.8
2	2280	6.1	14.0	2430	4.6	14.7	2700*	5.5	14.8	2730	4.4	15.2
3	2190	5.9	14.2	2430	5.1	14.4	2535	5.0	14.8	2730	4.7	15.2
4	2130	6.3	14.2	2400	5.3	14.4	2652	5.4	15.0	2730	4.5	15.4
5	2070	6.1	14.2	2130	5.2	14.5	2618	5.0	14.7	2715	4.3	15.4
6	2340	5.1	14.5				2685	5.1	15.2	2745	4.4	15.4
7	2370	4.9	14.6	2280	5.2	14.5	2715	4.5	15.0	2785	4.4	15.4
8	2310	5.2	14.6	2310	5.2	14.6	2730	4.3	15.5	2715	4.3	15.4

*questionable data, stripchart problem.

abnormally high differences in gaseous concentrations measured from various points during these tests. It was noted in the test logs that decreases in SO_2 concentrations from one point to another were as much as 10 to 15 percent while O_2 concentrations remained constant or decreased also. Since the gas has very low sulfur content and is fed into the boiler at different locations than the high sulfur coal these variances in concentrations would be a logical observation if stratification did exist. The data would further strengthen the concept that variations in fuel flow or air/fuel ratio at the burner do not mix sufficiently well to create a uniform gaseous mixture. However, stratification due to incomplete mixing seems to exist even though Reynolds number calculations and turbulent flow characteristics imply it should not. There is no doubt from the data that stratification due to air leaks and incomplete gas mixing at the burners exists within the economizer.

A third series of stratification test was performed at the inlet to the ESP to determine if the combustion gases are still stratified at the ESP and hence a potential cause for changes in ESP collection efficiencies different than those resulting from theoretical predictions.

Since it was not possible to have two sampling systems (one to monitor stratification between points and one to monitor variations at a single point due to boiler variations) two tests were run sampling at one point but employing the same procedure as would be used while testing for stratification during multipoint testing.

As described earlier, the ESP inlet flow is divided into two separate ducts. Instead of traversing the ESP inlet, the tests were run by determining one sampling location, on each side of the ESP, selected such that the data would be unaffected (or affected as little as possible) by air leakage. The sampling was then alternated between these points. Though not a point by point measure of stratification this would measure it on a large scale.

Initial traverses to determine the proper points at which to locate the sampling nozzles so as to obtain samples unaffected by ambient air leaks determined that there was stratification of gases in the ESP inlet caused by air leakage. This type of stratification was confined to an area near the ESP walls and was only present during times when the inlet was under negative pressure. This implies the air leakage was localized near the ESP inlet.

The identification of stratified combustion gases entering the inlet which were not caused by air leakage near the sampling area was not conclusive. Table 71 gives the results of tests used to determine background variations at the individual sampling points. Table 72 shows the variation of gaseous concentrations from gases entering each side of the ESP. As can be seen from the tables the differences in concentrations between the two sides of the ESP did at times (2 tests) exceed the maximum expected differences found by sampling

TABLE 71. "TEST TO DETERMINE TYPICAL DIFFERENCES OF RESULT FROM ONE POINT OVER TIME"

Series A - sampling from ESP side one only (all under constant operating conditions)

TEST #	A_1	A_2	A_3	A_4	A_5	Average	% Variance*
SO_2 ppm	2010	2018	2033	2014	1988	2013	2.2
O_2%	6.08	6.0	5.8	5.94	5.69	5.9	4.7
CO_2%	13.97	14.02	14.13	14.08	14.10	14.06	1.1

Series B - Sampling from ESP side two only

TEST #	B_1	B_2	B_3	B_4	B_5	Average	% Variance*
SO_2 ppm	1727	1677	1722	1690	1713	1706	2.6
O_2%	8.44	8.00	8.00	7.97	8.21	8.12	5.8
CO_2%	13.0	13.16	13.07	13.10	12.97	13.06	1.5%

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*Defined here as (Maxium Reading - Minumum Reading)/Average and is a measure of the maximum expected difference.

TABLE 72. TEST FOR COMPARISON BETWEEN ESP SIDE ONE AND TWO

TEST SERIES	C_1			C_2			D_1		
ESP SIDE	1	2	% difference	2	1	% difference	1	2	% difference
SO_2	1979	2037	2.9	2040	2050	0.5	1796	1778	1.0
O_2	16.53	6.25	4.4	5.84	5.89	0.9	8.06	8.0	.7
CO_2	14.23	14.13	0.7	14.05	13.95	0.7	12.97	12.78	1.5

TEST SERIES	D_2			E_1			E_2		
ESP SIDE	2	1	% difference	1	2	% difference	2	1	% difference
SO_2	1815	1740	4.2	2002	1997	0.3	1968	2027	3.0
O_2	7.91	8.63	8.7	6.13	6.09	0.7	6.08	6.5	6.7
CO_2	12.80	12.33	3.7	14.08	13.9	1.3	13.78	13.6	0.9

TEST SERIES	F_1			F_2			F_3		
ESP SIDE	1	2	% difference	2	1	% difference	1	2	% difference
SO_2	1930	1911	1.0	1971	19.87	1.0	1947	1955	0.4
O_2	6.56	6.1	7.2	6.5	6.4	1.5	6.3	6.0	4.8
CO_2	13.9	13.93	0.2	13.65	13.65	---	13.5	13.8	2.2

one point, implying possible stratifications. However, these differences for the majority of tests were below the expected maximum differences which would tend to imply no stratification. The result was that this type of stratification is not normally present at the ESP inlet or below detectable limits for the measuring system. In any case it is felt that the difference in gaseous concentrations at these locations are not large enough to cause any serious degradation to the Cat-Ox ESP.

This test series identified problems of gas stratification due to dilution of the combustion gases with air along the walls of all three sampling locations tested. Stratification of combustion gases not due to air leaks could only be positively verified at the economizer location. The data indicated that this stratification arises from differences in fuel/air ratio or fuel type being feed into the individual burners of the boiler.

The magnitude of the stratification indicates that the stratification will have little effect on ESP performance (excluding very large air leaks such as open ports). However, the effect on sampling results could be significant if multiple sampling points are not employed or at least a preliminary traverse perform to determine points of average concentration.

Material Balances--The concern of this task was to determine material balances for sulfur dioxide, sulfur trioxide, sulfates and trace elements. The task involved the performance of sulfur, SO_2, SO_3 and sulfate balances in an initial test series since the analysis of the collected samples would be less effected by contamination problems then would be the analysis for trace elements. Once sufficient data were collected to produce a sulfur and sulfur product balance, another series of tests would be run with much more care in sample handling and would require specialized sampling equipment to develop a trace element and toxic material balance. To determine the material balance, samples of all input and output materials will be extracted from the following locations.

- Coal samples after mill (as fired)
- Slag samples
- Mechanical collector
- ESP sample (collected material from hoppers)
- Particle emission sample
- Gaseous SO_2/SO_3 sample

The coal samples were to be collected at the output of the mills and would be integrated over the test period. The ASTM method described in earlier base line test documents were to be employed here. All samples were to be packaged for shipment immediately after each test.

The slag samples and mechanical collector samples were to be made up of combined grab samples taken some time after the start of the test and one taken near the end of the test. These samples were then to be packaged for shipment immediately after each test.

The individual ESP ash samples were to be collected from a number of different stages in the precipitator and would not have been combined. By analyzing samples from successive stages, it must have been possible to determine the uniformity or non-uniformity of sulfur content of the particulate material in the ESP. Samples from each stage were to be taken after the beginning of the test and prior to the end and then integrated before packaging for shipment.

The SO_2/SO_3 samples were to be extracted from the gas stream by the EPA Method 8. The solution samples were to be recovered according to Method 8 for later analysis on site. Since only one EPA train was available and was to be used for the SO_2/SO_3 tests, a second train (ASTM type) was to be borrowed form Illinois Power Co. for use as the particle collection train. The train was modified by replacing the thimble filter with an in stack fiberglass disc filter. The small weight of the fiberglass filter would require less of a collected sample weight size for accurate results. It would also make the system more comparable to EPA Method 5.

The volume flow data and mass loading data were to be measured and computed before the particulate sample was shipped out for analysis to an independent lab along with the other solid samples.

The plant operating data would have been recorded 3 times during the test. The test was to be run on a non-interference basis; the parameters were to be recorded but IPC would not have been requested to change them for the test.

All operational instruments were to be running during the test. The data were to be recorded on strip charts and analyzed on site after the testing was completed. Analysis of manual SO_2 and SO_3 samples were also to be performed on site.

The initial number of tests required would depend on the plant operating parameters and sampling conditions. Under optimal conditions (uniform operating parameters and sampling conditions) for tests would adequately represent the system. If the system load or fuel changes, eight tests could produce enough data to determine representative values for a sulfur balance, including SO_2, SO_3 and sulfates. The material balance for those elements would probably require a greater number of tests as well as more uniform and constant plant operating conditions since sampling times will be longer. This is the result of the requirement for longer samples and more careful sampling techniques to assure reproducible, accurate and measurable samples.

The scheduled test series was never run. During the period of time when equipment and manpower were available, IPC was employing a mix of high and low sulfur coal in Unit 4 (they were buying low sulfur coal and using their stock of high sulfur coal). By the time the unit was operating normally, the EPA sampling train was no longer available.

However, some initial data were collected to determine ranges of measurements. (See Table 73 for the results of this data collection.)

Expected trace element concentration ranges for the coal, slag, mechanical collector ash, and hopper ash were determined in the baseline study. Preliminary values for the ESP outlet particulate matter and the ESP collected fly ash were determined from two samples taken by The MITRE Corporation for analysis. Dow Chemical Company Contract Research Department personnel had the samples analyzed. The results are presented in the following section.

The preliminary test results were in the expected ranges. The data should only be considered as preliminary since the required sample handling procedures could not be employed (the outlet sample was collected by a stainless steel sampler hence some contamination of elements from stainless is expected).

Particle Size vs. Element Content--The objective of this task was to investigate the relationship between particle size and element content of fly ash and from a coal fired boiler. Theoretical predictions as well as tests results from the ESP tests discussed earlier in Section V indicate that ESP collection efficiencies vary with varying particle size. If the elemental content varies with particle size in such a manner that size ranges that indicate poor collection efficiencies have elevated levels of toxic trace elements then there could be a potential environmental problem employing the

TABLE 73. EXPECTED RANGES OF SULFUR BALANCE PRODUCED FROM THE SAMPLING LOCATION BASED ON INITIAL TEST DATA

	SO_2	SO_3	SO_4	S
Stack	0.2-0.28%	5.40 ppm	-	-
Particle from Stack	<0.0003 ppm	<0.3 ppm	2.9%	-
Range from Slag Hopper Ash Mechanical Collector ESP Collector Ash	-	-	-	0.3-0.6%
Coal	-	-	-	3.2-3.8%

specific collecting device to that particular particle emission problem.

The potential problem areas, however, are not limited to ESP's. All conventional particle collection equipment has demonstrated a sensitivity to particle size. Figure 31 gives a simplified relationship between particle size and collection efficiency of various systems. In actuality, the variation is not as uniform or as simple as shown here; however, the basic trends are generally considered correct. The ESP test section gives the specific relationships for the Cat-Ox ESP.

Samples of the IP Unit 4 emissions were to be taken from three locations:

- The Input to the ESP
- The Material Collected in the ESP
- The Stack for Total Emitted Fly Ash

Material collected at the ESP inlet and stack would have been sized during collection. Sampling times would have to be long to collect enough sample in each range to allow for accurate analysis. The samples of material collected by the ESP would have to be sized after collection. Separate samples were to be collected from each stage of the ESP to determine if any size segregation occurred during collection. All samples were to be analyzed for various trace elements and compounds, primarily those of high toxicity on potential carcinogens.

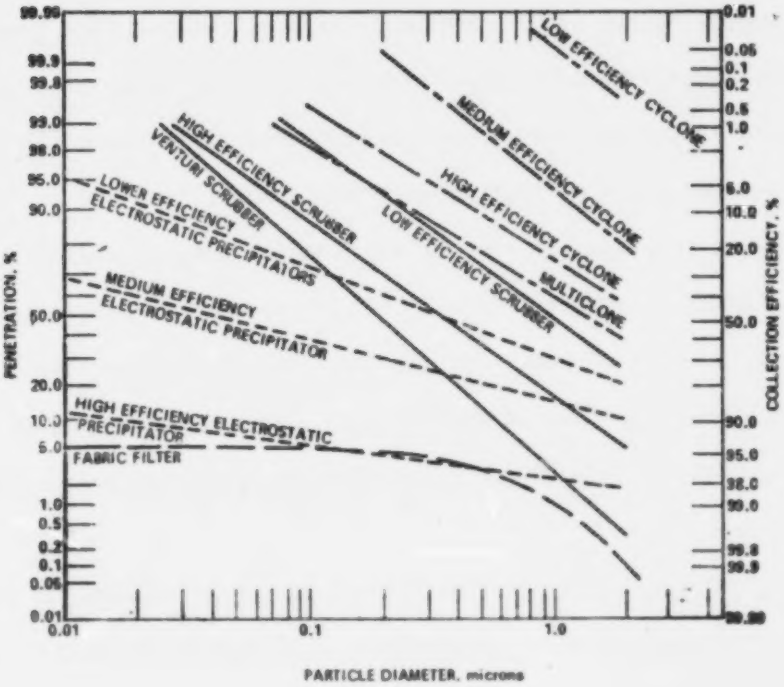

FIGURE 31. EXTRAPOLATED FRACTIONAL EFFICIENCY OF CONTROL DEVICES

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*Extracted from Proceedings: "The User and Fabric Filter Equipment Specialty Conference," Niagra Falls Frontier Section, APCA, October 1973, page 20.

The results obtained from the ESP inlet samples would typify the emission of a coal fired boiler and mechanical separation of this type. Comparing the trace element content of various size ranges of this sample with expected collection for the size range of a specific collection system may have an important input to determine if that system is applicable to this type of emission.

Samples from the ESP and the stack would give an indication to the magnitudes of effect that size has on collection efficiency and hence in emission rates for specific trace elements. Table 74 would be typical of these data, however, some contamination of the ESP outlet (stack) sample due to a stainless steel collector might have occurred.

This test series as outlined here would also indicate if the size range or elemental content of material collected in the ESP differs from ESP collection stage to collection stage.

Comparison of element content vs. size range between ESP inlet and stack samples plus the size variation with mass for the same samples give an indication if any collection efficiency variations might be an effect or more affected by the actual elemental content rather than size. This could be the case if looking at a simplified hypothetical case the inlet sampie showed 50 percent of the sample was greater than 5μm of which 0.03% was Zn while a hypothetical stack sample indicated the greater 5μm range was 0.001 percent Zn. This might then imply that the greater the 5μm portion of the sample is nonuniform in

TABLE 74. REPORT OF PARTICLE ANALYSIS***

	Electrostatic Precipitator 10-29-75	Electrostatic Precipitator Outlet (Stack)
% Silica (SiO_2)	52.1	44.2
% Calcium (CaO)	2.8	2.5
% Magnesium (MgO)	1.0	0.9
% Total Sulfur (S)	1.0	4.4
% Sodium (Na)	0.74	0.52
% Potassium (K)	2.1	1.7
% Lithium (Li)	0.012	0.008
% Sulfides (S)	0.0003	0.0003
% Sulfates (SO_4)	2.9	13.1
% Sulfites (SO_3)	0.3	0.3
% Chlorides (Cl)	0.008	0.015
% Aluminum (Al)*	26	20
% Iron (Fe)*	6.2	5.6
% Boron (B)*	0.13	0.13
% Titanium (Ti)*	1.1	0.9
% Vanadium (V)*	0.03	0.03
% Copper (Cu)*	0.0012	0.0015
% Chromium (Cr)*	0.028	0.16
% Beryllium (Be)*	0.00001	0.00001
% Zinc (Zn)*	0.028	0.028
% Lead (Pb)*	0.003	0.003
% Cadmium (Cd)*	0.0001	0.0001
% Arsenic (As)*	0.001	0.001
% Antimony (Sb)*	0.001	0.001
% Manganese (Mn)*	0.026	0.032
% Nickel (Ni)*	0.0052	0.084
% Tin (Sn)*	0.001	0.001
% Barium (Ba)*	0.001	0.001
% Fluorides (F)	0.017	0.086
% Total Carbon (C)	0.8	0.5
% Nitrites (NO_2)**	0.096	0.092
% Nitrates (NO_3)**	3.4	16
% Ammonia-Ammonium Nitrogen (NH_4)**	0.09	0.15

* By Emission Spectroscopy

** By Ion Chromatography - All other values were by Chemical Methods

*** Performed by Dow Chemical Co., Texas Division element content and the ESP collection efficiency favors the high Zn particles in that size range. There is no basis for the above hypothesis; however, it does demonstrate the type of information that could be correlated and determined from a comprehensive test of this nature.

This type of test could draw correlations between:

- Particle size vs. elemental content of uncontrolled boiler emissions
- Particle size vs. collection efficiency for a given collecting stage
- Elemental content vs. particle size for a given collecting stage
- Elemental content vs. collection efficiency for a given size range

The data could be valuable in evaluation of ESP applications to specific technologies as the evaluation of the use of various control techniques on coal fired boilers.

The data discussed earlier were only from two samples, one from the ESP outlet and one of the ESP. Neither sample was sized. The general analysis did indicate some minor differences in constituent content; however, some of the differences could be related to the sampling methods.

Test Support--The continuous monitoring system and MITRE staff cooperated with IP on a number of tests that they ran. During these tests, MITRE operated the SO_2, CO_2 and O_2 analyzers for a requested time period and presented the new data to IPC. The tests were performed on Wood River Units No. 4 and No. 5.

Similar test support was given during the testing of Unit No. 4 for the RAPS* program. Raw data on SO_2, CO_2 and O_2 concentrations were given to the sampling personnel after the test.

MITRE performed some preliminary tests on the external burner. The objective of the tests were two fold:

1) to test a special EPA water cooled probe constructed for the official burner tests, and

2) to assist MEC personnel in evaluating the Coen burner performance by obtaining particle data during set-up operations.

The tests indicated the probe would not cool uniformally in the original configurations. The probe was modified to correct the problem. Later tests indicated the modifications were adequate.

A total of three particle samples were taken. The raw data were given to Monsanto personnel on site and was used to determine what burner configuration produced the best results.

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*RAPS, Regional Air Pollution Study.

CORROSION TESTING

Corrosion due to the Cat-Ox environment was to be evaluated in two ways. The primary evaluation was to be from a planned test program while the secondary method was through observations of corrosion of actual equipment.

Corrosion Test Program

Corrosion rates are measured by the weight loss method as suggested in 1971 ASTM Book of Standards section G-1, Preparing, Cleaning and Evaluating Corrosion Test Specimens, and G-4, Recommended Practice for Conducting Plant Corrosion Tests. Corrosion specimens were installed at 11 locations throughout the Cat-Ox process. Ten locations were maintained and analyzed by MITRE and one location was maintained by Illinois Power Company personnel.

Selection of the materials to be tested was based on the following criteria:

(a) Material was used in the Cat-Ox system

(b) Material is frequently used for simlar application

(c) Material is well known for its corrosion resistance

(d) Material was recommended by manufacturer.

The major metals used in the Cat-Ox system include; C-1008 carbon steel, cor-ten steel, carpenter 20 stainless steel, chemical lead, USS T-1, and dur-iron. The carbon steel C-1008 is used throughout the process as ducting for the flue gas, structural support, piping for acid, and storage containers for acid. When used in acid or high SO_3 areas it is lined with teflon, chemical lead or a refactory. Carpenter 20 stainless is used in a number of acid pipes and pumps usually after the acid passes the product cooler. Cor-ten is employed in the Cat-Ox ID fan and the external burner by-pass. The lining of the absorbing tower is chemical lead. Dur-iron is used in the acid recirculation pumps where temperatures are too high for Carpenter 20 to be used. USS T-1 makes up a portion of the ID fan.

Other materials to be tested included AISI Type 316 stainless steel, Armco 22-13-5 stainless steel, modified Cor-ten A, alonized C-1008 carbon steel, Incoloy alloy 825, Inconel alloy 625, Monel alloy 410, and Uniloy LR-HL alloy. Table 75 lists all materials tested and their composition. Table 76 lists the locations where corrosion racks were placed, temperature and conditions as well as materials tested at each location. The materials listed in Table 76 were the coupons initially installed, some were added or deleted during the test program.

Testing Procedure

Prior to insertion into the Cat-Ox process, all specimens were cleaned with soap and water, and then acetone. The samples were weighed to the nearest 0.1 mg and mounted on specimen racks. The support rod for the specimens was 316 stainless steel. The specimens were insulated from each other by teflon sleeves which fit between the

TABLE 75. ELEMENTAL CONTENT OF TEST SPECIMENS (WEIGHT %)

No.	Type	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	
1	AISI, 316 Stainless	.06	1.25	.028	.014	.52	.13	12.0	17.6	2.63	.040 N
2	Carp. 20 C63	.027	.24	.021	.003	.42	3.22	33.66	19.61	2.36	.84 Cb + Tu
3	ARMCO 22-13-5	.044	5.28	.027	.007	.45	—	12.52	21.10	2.14	.16 V .14Cb .28 N
4	USS Cor-ten A	.11	.39	.098	.026	.44	.36	.33	.66		
5	Mod. Cor-ten A	.09	.38	.006	.024	.34	.27	.31	.63	.009	.091 Zr
6	A-36 Steel (C-1008)	.10	.38/ .50	.035 Max	.045 Max						
7	Chemical Lead										
8	USS T-1 Type A	.12 .21	1.0	.035	.04 Max	.20 .35			.40 .65	.15 .25	.03 .01 .0005 .08 U .03 T .005 B
9	Alonized C-1008										
10	Incoloy Alloy 825	.03	.5	-	.015	.25	2.5	42	21.5	3	30 Fe, .9T., .1 Al
11	Inconel Alloy 625	.05	.25	-	.008	.25	-	61	21.5	9	2.5 Fe, .2T:, .2 Al
12	Monel Alloy 400	.15	1	-	.12	.25	31.5	66.5	-	-	1.25 Fe
13	Uniloy LR-HC	.018	.48	.005	.007	<.01	<.01	Balance	15.13	15.97	3.76 W, <.001 Sn Pb, <.01 Zr Co, .26 V
14	Hasteloy C-276	.02	1.0	.03	.03	.05	-	Balance	14-16.5	15-17	4-7 Fe, 3-4.5 W, 2.5Co, .35 V
15	Copper										
16	Dur-iron	1.0	0.7			14.5			4-5%		remainder iron

TABLE 76. CORROSION TEST LOCATIONS AND CONDITIONS

POINT	LOCATION		CONDITION	TEMPERA-TURE	MATERIALS*
3	Electrostatic precipitator outlet	@ 4th 6" port	Flue gas	310	1 thru 6 and 9
4	Flue gas to gas heat exchanger (downstream of burner A)	@ a 4" port opposite side from rakes	Flue gas	350	1 thru 9
5	Flue gas from gas heat exchanger	@ 4th 6" port	Flue gas at high	776	1 thru 6
8	Flue gas from converter	@ 4" port below robes	Flue gas plus SO_3	850	1 thru 6 and 8 thru 13
10	Flue gas to absorber	@ 4" port on top of ducting	Flue gas plus SO_3 at lower temperature	440	1 thru 9
11	Flue gas from demister	@ 6" port 2nd from right	Flue gas SO_x removed	249	1 thru 9
13	Flue gas to stack (downstream of new I.D. fan)	@ 6" port	Flue gas SO_2 removed	249	1 thru 6 and 8, 9
A	Acid from absorbing tower	@ Blanking plant	Acid	282	Illinois Power
B	Recirculating acid to product cooler	@ Blanking plant with special valve	Acid	205	1 thru 13
C	Acid from product cooler	@ 3 diameter above pumps	Acid at lower temperature	100	1 thru 7 9 thru 13 and 16
D	Absorber (mist eliminator)	@ mist eliminator on filter	Acid and flue gas	205-440	1 thru 8

*Numbers referenced Table 75

sample and the rod. Larger diameter teflon spacers were used to keep the specimens apart. Due to temperatures in excess of 600°F at Points 5 and 7, glass sleeves and asbestos spacers were used in place of teflon. This method of mounting the specimens was to prevent damage to or loss of specimens by causes other than corrosion as well as eliminate the possibility of galvanic effects caused by metal to metal contact of specimens or between process elements and the specimens. Coupons were removed for inspection periodically with the exception of the rack in the absorbing tower and the rack in the acid pipe from the absorbing tower. These two locations could only be inspected during those times when the process was not operating. The condition and appearance of the holder and specimen were carefully noted. The specimens were photographed, reweighed and replaced. An additional examination under low magnifications was performed to check for localized corrosion. The photographs of the clean specimens served as a record of the surface appearance. A written record was kept on the appearance and adhesion of any coatings or films on the surface of the specimen.

Samples were cleaned prior to weighing by the following procedure:

(1) Coupons were cleaned with acetone to remove organic deposits.

(2) Coupons were scrubbed with a fiber brush and mild soap.

(3) Should electrolytic cleaning be required, the coupons were to be immersed in a 5 percent (weight) sulfuric acid solution to which 0.2 percent by volume of organic inhibitors has been added. Solution temperature were to be 165°F. A carbon anode was to be installed and a cathode current density of 2000 amps/sq. meter would be maintained for 3 minutes.

To check for possible weight loss due to the cleaning method at least one sample was cleaned, weighed and recleaned and weighed again. A lower weight after recleaning was considered cause to suspect the cleaning method of removing some base metal. Appropriate measures were taken to correct for this error if it existed.

After inspection, the samples were replaced in a different order for the next three month period to minimize errors resulting from symmetric location of the sample on the rack.

Due to space limitations, no duplication of specimen type was possible at any one location. However, as the test program proceeded, certain samples proved to be inferior early in the program (by the first 2 inspections) these samples were replaced by materials used in the Cat-Ox process wherever possible. Specimens of metals used in the Cat-Ox process were of specific interest since they could give insight to the expected life of materials and equipment.

Visual examination of Cat-Ox equipment was made whenever possible. These inspections were to supplement actual measurement and provide additional information relating to pitting or localized corrosion.

For identification purposes, a record was kept of the relative position of the test specimens on the holder. Therefore, if identification marks were obliterated by corrosion, careful handling would have maintained sample identity. The primary identifications were made by means of stamped code numbers on each sample. The stamped number gives additional information in that a specimen showing preferential attack at the stamped area is an indication of that specimen's susceptibility to corrosion when coldworked. This information was useful in determining if special testing relative to coldworked materials was warranted. While the presence of this localized attack is a positive indication of the material's susceptibility, the absence of attack is not a guarantee of immunity to attack, particularly with regard to equipment.

A distinction was made between pits and localize corrosion occurring under or at the insulating spacers as opposed to the exposed surfaces. Pitting at or under the insulating spacers is an indication of the susceptibility of the material to "concentration cell" effects while pitting on the surface indicates the intrinsic corrosive nature of the environment. It should be noted that even severe pitting is not sufficient grounds for rejection of a material only an indication of the need for further testing.

Calculation of Corrosion

The corrosion rate is calculated from the equation:

$$C=[(W_i - W_f)/\rho At]$$

where

C = Corrosion rate (cm/day)
W_i = Initial weight of specimen (gm)
W_f = Final weight of specimen (gm)
ρ = Density of specimen (gm/cm^3)
A = Surface area of specimen (cm^2)
t = Duration of test (days)

If the density is eliminated from the equation, the corrosion rate can be represented in mg/mm^2-day or weight loss per area and time which is also an acceptable representation.

Weight loss is a suitable method for measuring corrosion if the corrosion is uniform. When significant pitting or localized corrosion occurs, measurement of pitting depth by a depth gage, micrometer calipers, or microscope may be more useful. A pitting factor ratio is the ratio of the deepest metal penetration to the average metal penetration as measured by the weight loss method.

Results From First Test Period (August 1974 - March 1975)

The conditions listed in Table 76 apply when the Cat-Ox unit is operational. During this test period the unit operated less than one week. The actual conditions experienced at each location and appearance of the sample coupons are described in Appendix C. The corrosion rates calculated in this period can therefore be assumed to be representative of corrosion during inoperable phases.

The initial dimensions and weights for all coupons prior to exposure are given in Table 77. The length, width or diameter of all

D = Diameter ± 1/64"
LxW = Length & Width ± 1/64"
T = Thickness ± .001"
Wt = Weight in grams

TABLE 77. INITIAL MEASUREMENTS OF SAMPLES

Coupon Number	Point 3			Point 4			Point 5			Point 10			Point 11		
	LxW	T	Wt	LxW	T	Wt	LxW	T	Wt	LxW	T	Wt	L&W	T	Wt
1	2	.122	60.5406	1.984	.123	60.4548	1.984	.124	60.8008	2	.122	60.3297	1.984	.121	59.6630
2	2	.130	65.2732	1.984	.129	64.9381	1.984	.134	66.9018	1.984	.128	64.1425	1.984	.128	64.1011
3	1.984	.117	54.6652	1.953	.117	54.2835	1.953	.116	54.0630	1.953	.117	54.6391	1.969	.117	54.5473
4	2	.122	59.3054	1.984	.122	59.0471	1.984	.123	59.4252	2	.122	59.3925	1.984	.123	59.3931
5	2	.102	48.9226	1.984	.102	48.9894	1.984	.102	49.1383	2	.102	49.0570	1.984	.102	48.8649
6	2	.133	65.1515	2	.133	64.8693	1.984 x2	.134	65.3785	2	.134	65.4236	2	.134	65.1810
7	2	.082	56.1697	1.984	.075	51.2764				1.984	.076	51.4701	2	.072	50.8789
8				1.875	.205	87.7236				2.031	.210	101.9234	2	.205	100.0267
9	2x2.031	.139	64.8900	2x1 .953	.136	62.6735				2.031 x2.063	.136	63.1919	2	.132	63.8938
10															
11															
12															
13															
14							D = 2.219*	.038	20.7201						
15															
16															

*Installed after the 1st Inspection (about March 1975)

D = Diameter, inches ± 1/64
LxW = Length & Width Inches ± 1/64
T = Thickness, Inches ± 1/1000
Wt = Weight, grams

TABLE 77. (Continued)

Coupon Number	Point 13			Point "B"			Point "C"			Point "D"**			Point 8*		
	LxW	T	Wt	D	T	Wt	LxW	T	Wt	LxW	T	Wt	LxW	T	Wt
1	1.984	.122	60.3654	1.234	.123	16.4078	1.984	.123	60.6629	2	.121	59.8302	2	.123	60.5013
2	1.984	.134	67.4002	1.234	.130	17.6418	1.984	.134	66.8597	2	.131	65.9454	2	.132	65.7984
3	1.938	.117	54.1547	1.234	.117	15.4812	1.938	.116	54.0926	1.875	.117	54.5860	1.938	.117	54.6110
4	1.984	.123	59.4024	1.234	.123	15.9452	1.984	.122	59.3842	2	.122	59.3598	2	.122	59.3701
5	1.984	.102	49.0159	1.234	.103	13.3420	1.984	.102	48.9435	2	.102	49.3501	2	.103	49.4223
6	1.984	.134	65.1787	1.234	.126	17.6561	1.984	.134	65.2592	2	.133	65.2021	2	.134	65.4078
7	1.984	.083	55.9968	1.234	.059	11.2080	2	.073	50.7757	2	.082	56.2211			
8	1.891	.219	94.0102							1.875	.219	93.9338	2	.205	101.3501
9	2x2.031	.132	63.6742				2x1.938	.132	62.2933	1.031	.133	63.1189	2x2.031	.140	64.6319
10							1.234D	.124	25.4724				1.5D	.123	25.2999
11							1.234D	.130	27.8973				1.5D	.131	27.8923
12				1.219*	.138	20.2405	†1.984D*	.137	57.7793				1.5D	.138	30.6931
13							1.984	.109	59.5047				1.938x 2.031	.108	59.4540
14				1.234*	.039	5.6776	2.219D*	.039	21.0294						
15				1.250*	.249	37.2459	1.98D*	.248	105.9420						
16				1.047	.241	23.1737									

*Installed after First Inspection (March 1975)

**Not Removed for Weighing During this Period

†New Sample Polished for Experimental Purposes

samples tested did not change a measurable amount with the exception of samples 4, 5, and 6 at Point "B". Coupons 5 and 6 were totally destroyed while 4 decreased by 0.1 inches. Table 78 gives the thickness and final weight of the coupons from each location where the racks were removed and analyzed.

Table 79 gives the calculated corrosion rates of the specimens at the location tested. The corrosion rates are presented in metric units (cm/day). The more frequently used units are the English mils per year (mpy) where:

$$1 \text{ cm/day} = 1.437 \times 10^5 \text{ mpy}$$

A metal exhibiting 1 mpy (6.96×10^{-6} cm/day) is generally considered to have high resistances to the corrosive products. A rate from 0.5 to 5 mpy (3.5×10^{-6} to 35×10^{-6} cm/day) termed good resistance and 2 to 10 is (14×10^{-6} to 70×10^{-6} cm/day) moderate resistance. The terms "fair resistance" or "moderate attack" imply corrosion to about 60 mpy ($\approx 420 \times 10^{-6}$ cm/day).

The largest corrosion rates were for the Cor-ten and carbon steel samples at Point "B". The corrosion rates for these coupons were excessive and, as a result, the metals were rejected for this application. Locations 10, 11 and C experienced more corrosion than the other areas; however, no samples showed enough of a rate to be rejected on the first test period. Samples 2 and 3 at Point C and sample 4 at Point 4 experienced no measurable corrosion. Sample 7 at Points 3 and 13 showed a weight gain caused by the surface of the samples being impregnated with fly ash due to the high temperatures

TABLE 78. THICKNESS AND WEIGHT AFTER EXPOSURE FOR FIRST TEST PERIOD

Coupon Number	Point 3		Point 4		Point 5		Point 8		Point 10		Point 11		Point 13		Point "B"		Point "C"	
	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram	T Inches	Wt gram
1	N.C.	60.5338	N.C.	60.4439	N.C.	60.7999	N.C.	60.4914	N.C.	60.2586	N.C.	59.2686	N.C.	60.3599	N.C.	16.4060	N.C.	60.6554
2		65.2619	N.C.	64.9188		66.8879	N.C.	65.7814		64.0944		63.1929		67.3994	N.C.	17.6385	N.C.	66.8633
3		54.6563	N.C.	54.2693		54,0617	N.C.	54.6013		54.5818		54.2255		54.1515	N.C.	15.4781	N.C.	54.0956
4		59.2000	.124	59.0560		59.4224	N.C.	59.2998		59.0369	.130	58.6864		59.1515	.06	3.7583	.121	55.6875
5		48.8815	.105	48.9885		49.1291	N.C.	49.3753		48.3291	.109	47.7530		48.9827	0	0	.100	47.2034
6		65.0758	.136	64.8677	N.C.	65.3530	N.C.	65.3084	N.C.	64.9200	.142	63.5579		65.1422	0	0	.132	62.4704
7	N.C.	56.6362	.074	51.2709						50.3937	.073	50.8080		56.0906	N.C.	11.1694	.073	50.7680
8			.207	87.7236			N.C.	101.2672		100.9619	.212	99.6167		98.8816			.111	51.8934
9	N.C.	64.8725	.137	62.6735			N.C.	64.6306	N.C.	62.4690	.133	63.0428	N.C.	63.6368			N.C.	25.2869
10							N.C.	25.2966									N.C.	27.8584
11							N.C.	27.8939							New		N.C.	30.5037
12							N.C.	30.6931									.109	59.4998
13							N.C.	59.4502							New		New	
14					New										New			
15															N.C.	23.1130		
16																		

T = Thickness

Wt = Weight

N.C. = No Change from Initial Measurement

TABLE 79. CALCULATED CORROSION RATES
(cm/day x 10^{-6})

Coupon Number	172 Days @ Pt. 3	203 Days @ Pt. 4	229 Days @ Pt. 5	256 Days @ Pt. 8	200 Days @ Pt. 10	197 Days @ Pt. 11	99 Days @ Pt. 13	188 Days @ Pt. B	220 Days @ Pt. C	Density gm/cm^3
1	0.089	0.123	0.009	0.087	0.840	4.59	0.127	0.080$^{(2)}$	0.078	8.00
2	0.145	0.214	0.132	0.145	0.537	10.62	0.018	0.143$^{(2)}$	(1)	8.07
3	0.126	0.170	0.013	0.092	0.696	3.91	0.077	0.142	(1)	7.83
4	1.42	(1)	0.028	0.617	4.12	8.42	0.722	555.8	38.9	7.79
5	0.546	0.010	0.092	0.415	8.32	13.11	0.777	>550	18.1	7.69
6	1.01	0.018	0.25	0.871	3.58	18.80	0.796	>690	28.9	7.83
7	(1)	0.047			5.85	6.68	(1)	1.39$^{(2)}$	0.059	11.15
8		0.065		0.673	9.90	4.43	3.05			7.87
9	0.595	0.480		0.011	7.92	10.26	0.843		105.4	7.78
10				0.062					4.25	8.10
11				(1)					0.866	8.33
12				0.514				(3)	3.28	8.74
Polished				0.032					(3)	
12										
13									0.044	9.31
14			3					(3)	(3)	8.91
15								(3)	(3)	8.95
16								3.68$^{(2)}$		6.74

(1) Sample showed no weight loss or gained weight, see text
(2) Sample was damaged, coupon number 16 was damaged badly others seemed minor
(3) New coupon to rack

at those locations. Because of this and since no lead is used at 3, 4 and 13, it is felt that no useful information would be gained by having samples of lead at these points. Hence, the samples were replaced with more useful coupons during the next inspection.

In general, all the coupons at Points 3, 4, 5, 10, 11 and 13 exhibited high to good resistance to corrosion in the respective atmospheres. While at Points B and C the stainless steels, lead and nickel base alloys showed high resistance, the carbon steels and Cor-ten showed very poor to moderately good resistance.

Table 80 lists the weight and dimensions of the coupons (if changed) after the last test period. Tables 81 and 82 list the corrosion rates for all locations and coupons for the 2nd test period and the combined 1st and 2nd test period (over entire exposure time).

To aid in evaluating the results, Table 83 gives the corrosion rates of all metals at the respective points, for 1st, 2nd and combined tests in a qualitative form. The qualitative ranges are given below:

$> 1 \times 10^{-6}$ cm/day - very high resistance
$> 7 \times 10^{-6}$ cm/day - high resistance
4 to 35×10^{-6} cm/day - good resistance
14 to 70×10^{-6} cm/day - moderate resistance
60 to 420×10^{-6} cm/day - fair resistance moderate attack

TABLE 80. WEIGHT OF COUPONS AFTER SECOND PERIOD TEST

N.C. = No change of dimensions >.005 in.

	Pt. 3		Pt. 4		Pt. 5		Pt. 8		Pt. 10		Pt. 11		Pt. "B"		Pt. "C"		Pt. "D"	
	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm	Dem.	Wt. gm
#1	N.C.	60.5238	N.C.	60.4411	N.C.	60.7984	N.C.	60.4951	N.C.	60.2467	N.C.	59.2375	N.C.	16.4010	N.C.	60.6545	N.C.	59.4018
#2	N.C.	65.2600	N.C.	64.9187	N.C.	66.8840	N.C.	65.7792	N.C.	64.0827	N.C.	63.1437		17.6367	N.C.	66.8595	N.C.	65.3340
#3	N.C.	54.6560	N.C.	54.2689	N.C.	54.0583	N.C.	54.6109	N.C.	54.5695	N.C.	54.2221		15.4758	N.C.	54.0946	N.C.	54.1751
#4	N.C.	59.1124	N.C.	58.4360	N.C.	59.3549	N.C.	59.2860	N.C.	58.8150	N.C.	58.0292			N.C.	53.3504	N.C.	58.0041
#5	N.C.	48.8199	N.C.	48.2445	N.C.	49.0556	N.C.	49.3700	N.C.	48.2998	N.C.	47.0105			N.C.	46.6223	N.C.	48.5542
#6	N.C.	64.9209	N.C.	63.1328	N.C.	65.3321	N.C.	65.3071	N.C.	64.9028	N.C.	63.0437			N.C.	62.1833	N.C.	63.7104
#7	N.C.	56.6344	N.C.	51.2400					N.C.	50.3831	N.C.	50.6993	N.C.	11.1647	N.C.	50.7409	N.C.	56.2070
#8			N.C.	86.3395			N.C.	101.2576	N.C.	100.8103	N.C.	99.5028					N.C.	92.9802
#9	N.C.	64.8054	N.C.	62.2517			N.C.	64.6272	N.C.	62.3904	N.C.	62.7424					N.C.	62.5775
#10							N.C.	25.2956							N.C.	25.2769		
#11							N.C.	27.8925							N.C.	27.8450		
#12							N.C.	30.6833					N.C.	19.5924	N.C.	30.2436 57.0288		
#13							N.C.	59.4496							N.C.	59.4816		
#14					N.C.								N.C.	5.6754	N.C.	21.0181		
#15													N.C.	36.3733	N.C.	105.4654		
#16													N.C.	23.1063				

TABLE 81. SECOND TEST PERIOD - CORROSION RATES (cm/day x 10^{-6})

Location Coupon #	3 (319 Days)	4 (427 Days)	5 (392 Days)	8 (366 Days)	10 (200 Days)	11 (429 Days)	B (229 Days)	C (214 Days)	D (761 Days)
1	0.0707	0.0150	0.0088	0.0228	0.0658	0.1664	0.1827	0.0096	2.3813
2	0.0132	0.0005	0.0224	0.0134	0.0618	0.2592	0.0644	0.0399	3.3108
3	0.0023	0.0023	0.0211	0.0026	0.0698	0.0134	0.0867	0.0112	2.6687
4	0.6365	3.4500	0.4051	0.0859	1.2017	3.6037		25.3147	7.259
5	0.4621	4.2359	0.3877	0.0340	0.1642	4.2076		7.6164	4.7603
6	1.1086	9.2760	0.1274	0.0080	0.0917	2.7340		3.0602	8.2977
7		0.1245			0.0426	0.4321	0.1292	0.7072	0.0641
8		7.9039		0.0591	0.7293	0.5655			5.1746
9	0.2506	2.3715		0.0207	0.2998	1.5620			2.9412
10				0.0134				0.2376	
11				0.0181				0.0780	
12				0.1194			23.7625	5.7064 9.3621	
13				0.0034				0.1697	
14							0.1794	0.1149	
15							22.0255	5.2575	
							0.3304		

TABLE 82. COMBINED PERIODS CORROSION RATE DATA (cm/day x 10^{-6})

Location Coupon #	3	4	5	8	10	11	B	C	D
1	0.0781	0.0498	0.0088	0.0224	0.6893	1.5598	0.1364	0.0443	2.3813
2	0.0597	0.0695	0.0644	0.0687	0.2152	3.4925	0.1002	0.0010	3.3108
3	0.0455	0.0562	0.0183	0.0003	0.2691	1.2419	0.1118	N.C.	2.6687
4	0.9111	2.2839	0.2663	0.4991	2.1315	2.5642		32.26	7.259
5	0.5005	2.8744	0.3186	0.1975	2.0880	4.2874		12.7990	4.7603
6	1.0722	6.2928	0.1704	0.3629	1.8916	7.7878		16.1662	8.2977
7		0.0994			2.9761	0.4874	0.5368	0.1361	0.0641
8		5.2921		0.3090	3.6495	1.7824			5.1746
9	0.3712	1.6073		0.0132	2.7946	4.1029			2.9412
10				0.0338				2.2904	
11				N.C.				0.5914	
12				0.2827			23.7625*	2.8137 9.3621*	
13				0.0145				0.1061	
14			N.C.				0.1794*	0.1149*	
15							22.0255*	5.2575*	
16							1.825		

*Sample only in 2nd period

TABLE 83. QUALITATIVE COMPARISON OF COUPONS OVER FIRST AND SECOND TEST PERIODS

Location Coupon #	3			4			5			8			10			11			B			C			D		
	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com	1st	2nd	Com
1	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	H/G	V	H	V*	V	V*	V	V	V		H	
2	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	G	V	H	V*	V	V*	V	V	V		H	
3	V	V	V	V	V	V	V	V	V	V	V	V	V	V	V	H/G	V	H	V	V	V	V	V	V		H	
4	H	V	V	V	H	H	V	V	V	V	V	V	E/G	H	H	G	H	H	F			M	G/M	M		G	
5	V	V	V	V	H/G	H	V	V	V	V	V	V	G	V	H	G/M	H/G	H/G	F			G/M	G	G/M		H/G	
6	H	H	H	V	G	G/H	V	V	V	V	V	V	E	V	H	G/M	H	G	F			M/G	H	G/M		G	
7				V	V	V							H/G	V	H	G/H	V	V	H*	V	V*	V	V	V		V	
8				V	H/G	H/G				V	V	V	G	V	H	H/G	V	H								H/G	
9	V	V	V	V	H	H				V	V	V	G	V	H	G	H	H/G				F				H	
10										V	V	V										H/G	V	H			
11										V	V	V										V	V	V			
12										V	V	V								M/G		H	H/G G	H G			
13										V	V	V										V	V	V			
14																				V			V H/G	V H/G			
15																				M/G							
16																			H	V	H*						

KEY:
V = very high resistance
H = high resistance
G = good resistance
M = moderate resistance
F = fair resistance
(moderate corrosion)
* = damaged during 1st period

From Table 81 it can be seen that the only major corrosion during this period occurred at locations B, C, and D. Those coupons most affected included the Cor-tens and various carbon steels (coupon numbers 3, 4, 5, 8 and 9) plus copper and high copper alloys (15 & 12). Most of the specialty alloys did very well. Comparing corrosion rates here between period 1 and 2 in general, the corrosion rates over period 2 were less probably because of less exposures to acid during this period.

The only area where coupons 1, 2 and 3 did not show very high resistance was at location D, which is to be expected. These coupons were in place over the entire time period between test 1 and test 2. It is likely that most of the corrosion occurred during the first test period, when the acid was stored in the absorbing tower and the blanking plate to Cat-Ox near point 11 was open. Both these conditions seem to have caused accelerated corrosion conditions at point 10 and point 11, respectively. Table 82 points out the difference quite clearly, at point 10 during period 1. When acid gases, caused by the H_2SO_4 stored in the tower were present, corrosion rates were an order of magnitude higher on almost all coupons. At point 11 during the 1st period, when the blanking plate was open, corrosive elements of hot flue gas were able to condense out. During the second test period the plate was closed and no condensing was noted. As a result, corrosion rates were as much as three orders of magnitude less during the second period. Coupons 1, 2 and 3 make this especially apparent.

Location 4 showed the only inconsistent results. The stainless steel type metals (coupons 1, 2 and 3) indicated more corrosion resistence (not significant) in period 2 as would be expected since during attempted start-ups of period 1 this location was relatively cold when it was exposed to hot flue gases, causing condensation of corrosive products on the coupons. The Cor-tens and Carbon steel (4, 5, 6, 8 and 9), however, showed more resistence during the first period. At point 11 it was noted that coupons 1, 2, and 3 were more effected (percentage increase of corrosion rate was greater, but rate itself was not necessarily so) by the condensing flue gas than the coupons; however, both were effected adversely.

In locations 3, 5, and 8, Table 83 shows that there is very little change in corrosion rates between test periods. Again this is to be expected since conditions at these locations were much the same over both periods. The only difference was that the coupons were at higher temperatures for a short period of time during period 1 but this seemed to have no serious effect on corrosion.

All results discussed below are only for non-operational conditions and should not necessarily be a basis for selecting or recommending materials for operational conditions.

The results of these coupon corrosion tests seem to indicate that all the materials tested do well in non-operational conditions if not exposed to cold, acid gases or condensing flue gas.

Areas where acid is present require lead or specialty metals. Metals 4, 5, 6, 8, 9, 12 or 15 do not seem to stand up as well as the other samples.

In areas of acid gases and condensing flue gas only sample 1 through 9 were tested. Coupons 1, 2, 3 and 7 seem to hold up best. However, it is uncertain if the extensive pitting on coupons 1, 2, and 3 in the presence of condensing flue gas, might not be more of a problem than the slightly higher corrosion rates of the other samples.

Observations of Corrosion Activity

The purpose of this section is to record and describe the observations made relative to corrosion activity within the Cat-Ox system. All observations are based on non-operational conditions. Though Cat-Ox was operational for a short period, the length of such periods was insignificant compared with the total non-operational exposure. As a result the corrosion must be assumed the result of non-operational conditions. This does not imply that the conditions were less severe than operational conditions, only that they are different. The discussion is divided by major components of the Cat-Ox system:

1. Electrostatic Precipitator
2. Reheat Burner
3. Ljungstrom Gas Heat Exchanger
4. Catalyst Bed and Converter
5. ID Fan

6. Acid Recirculation System

7. Product Handling System

Electrostatic Precipitator--

The ESP is the only subsystem of Cat-Ox that was operational over the observation period. The unit showed no adverse effects resulting from corrosion.

Reheat Burner--

This subsystem was under ambient conditions for most of the time and it only operated during a few test runs and never at full capacity. There was no significant corrosion.

Ljungstrom Gas Heat Exchanger--

The gas heat exchanger displayed no sign of corrosion damage, though the supporting equipment and ducting to this subsystem showed some sign of light rusting but no significant damage.

Converter--

The converter did not operate over the observation period, however, the catalyst handling system experienced conditions which would be similar if Cat-Ox was operable.

The converter and catalyst handling system are in very good condition. The subsystem shows typical signs of weathering but no damaging corrosion.

Absorbing Tower--

The absorbing tower is in good condition from a corrosion standpoint. In general, it has not operated with the exception of previously described attempted start-ups and the period of time it was exposed to weak acid that was stored in this tower. The stainless steel and Carpenter 20 Components in the upper section of the tower showed some minor pitting. The pitting though a potential problem was not developed to an extent which could be considered structurally dangerous. Exposed carbon steel areas at the top of the tower showed moderate rusting but again no structural damage.

Main Cat-Ox ID Fan--

The fan is in basically good condition. There is a moderate amount of rusting in the fan and ducting but no serious damage.

Acid Recirculation System--

Though affected by other problems, the recirculating pumps are in good condition relative to corrosion. The supports and pit area for the pumps, however, are severely corroded. Condensing flue gas dripping into the pit area is the prime cause of the corrosion. Damage is severe enough to require complete replacement of pump structural supports and at least an overhaul of the pit area.

The graphite heat exchangers, which were prone to leaking (though not the direct result of corrosion), have experienced serious corrosion damage on the cooling-water side. The cooler steel baffles and tie rods are, in many cases, beyond repair.

The Teflon and Carpenter 20 cb-3 recirculation piping has shown no external traces of corrosion. It is suspected that the carpenter

20 cb-3 piping has suffered corrosion but the magnitude is difficult to access.

Product Acid System--

This subsystem has been most affected by corrosion. The conditions experienced have been probably more severe than if the unit were operational. As a result of unsuccessful start-ups and lengthy storage periods the system was exposed to very corrosive weak acid. The plain steel product piping, which was marginal for the designed 78 percent H_2SO_4 it was exposed to, continually leaked and had to be repaired. Similar circumstances existed for the carpenter 20 cb-3 product pumps which were also repaired (replaced impellers or castings) a number of times.

The storage tanks also suffered major corrosion damage. The south acid storage tank had a corroded area 21 inches wide 36 inches from the bottom of the tank which experienced a greater than 40 percent loss of the base metal. The north tank had a similar band only 1-3 inches wide about 5 inches from the bottom of the tower. These selective corrosion bands are again the results of weak acid which, in this instance, probably floated on the top of a slightly stronger layer of H_2SO_4.

Conclusions

In general the results of the corrosion test program agreed with the observations made on Cat-Ox equipment. All test materials and components within the Cat-Ox system showed good corrosion resistance with the exception of those areas that were exposed to acid, acid gases, or condensing flue gas.

In areas of acid exposure the stainless steel, Carpenter 20 cb-3, Inconel, Incoloy, monel, Duriron, uniloy, Hasteloy and chemical lead samples had the best corrosion resistance. Of the samples tested in condensing flue gas and acid gases the 2 stainless steels and Carpenter 20 cb-3 showed the least base metal loss; however, the large scale pitting in condensing flue gas area found on the samples might be more of a problem then the somewhat higher base metal loss of the other material.

SECTION VI

SIGNIFICANT RESULTS

PROCESS DESIGN

The tests preceding the Wood River demonstration, the 24-hour acceptance test of the Wood River system and various studies indicated that the Cat-Ox process is a technically viable process. Current technology for particle control is capable of meeting the inlet requirements for the Cat-Ox process in either the integrated or retrofit systems. The catalytic converter is capable of greater than 90 percent SO_2 to SO_3 conversion efficiency. The 77.7 percent H_2SO_4 concentration can be maintained during steady state and transient operation. Lengthy start-up conditions, however, may result in the generation of dilute hot H_2SO_4 which can cause a corrosion problem.

Economic comparison with Mag-Ox and Wellman-Lord/Allied FGD processes showed that the Cat-Ox process required the highest capital investment and the integrated Cat-Ox had the lowest annual operating costs. The Cat-Ox process was less sensitive to coal sulfur content than the other processes. However, Mag-Ox produced the least impact on the cost of electricity. The selling price of the acid and its "saleability" would have a significant effect on the Cat-Ox annualized costs. The primary market for the dilute impure acid is the fertilizer industry that consumes over one half of the sulfuric acid produced in this country and though the trace elements in the acid produced by Cat-Ox have not been shown to produce toxic health and environmental effects, more research is required before any final judgment can be made.

WOOD RIVER PROCESS DESIGN/OPERATION

Though the process design appears technically viable, the Wood River site was plagued with numerous operational problems. The problems were related to two basic areas:

- Design. Certain power plant or system characteristics or requirements of the power plant environment were not accounted for or identified in the initial design of the unit.
    - Internal reheat system would not function properly when the system was committed to use oil instead of gas. This resulted in lengthy start-ups.
    - Vibration in the power plant environment was assumed to cause breakage or wear of the graphite heat exchanger (primarily at a metal to graphite contact point in the tube bundle). Acid or water flow may also have contributed to the vibrations.
    - Dilute acid caused by lengthy start-ups resulted in serious corrosion in portions of the system.
    - Inability to isolate some equipment so it could be maintained with the system in service resulted in added shutdowns.
- Operation. Power plant personnel were unfamiliar with chemical plant operations and requirements.
    - Personnel were unfamiliar with the operating and maintenance requirements of special alloys, materials and equipment such as duriron recirculating pumps
    - Unfamiliarity with acid handling problems resulted in the corrosion of areas in the product handling system.

These problems combined to result in lengthy delays which further compounded the problems. In addition, long periods of shutdown had an adverse effect on the process and caused serious deterioration of some system components. The only system component which was operational and functioning without problems since its construction was the electrostatic precipitator.

A survey of the plant status indicated that the major problems outlined above or caused by system deterioration could be solved by a major restoration program. However, IPC has chosen to comply with SO_2 standards by burning low sulfur coal in the Unit 5 boiler and physical constraints prevent them from employing a different type of coal for Unit 4. The demonstration program would have to be run on low sulfur coal. Though the results based on low sulfur fuel operation would be useful, they would leave many serious questions about Cat-Ox operability unanswered. Hence, continuation of the demonstration would be of very limited use; accordingly, the program was discontinued.

As stated earlier, discontinuation of the program neither proves nor disproves the feasibility of the Cat-Ox system. However, some inferences from the experiences indicate that the Cat-Ox system would probably be more desirable as an integrated system application rather than in a retrofit situation. The benefits associated with the integrated system application are:

- the reheat system would not be required;
- there could be more advantageous placement of system components and elimination of long product lines and poor accessibility of some equipment; and

- the annual operating costs would be lower for an integrated Cat-Ox.

Furthermore, other more economical regenerable FGD systems have been demonstrated to a more advanced stage in retrofit situations. Little benefit could, therefore, be realized from the large expenditure to refurnish the retrofit Cat-Ox demonstration system.

TESTING

The only testing completed on an operational Cat-Ox was the 24-hour acceptance test which indicated that the system will meet design specifications. However, during the acceptance test the system did suffer from high pressure drops across the demister. The problem was probably caused by poor burner control of the internal burners which caused the evolution of soot and subsequent clogging of the mist eliminator packing. The results of this test and experiences that followed indicated that a longer acceptance test for future demonstrations may be desirable.

The baseline tests for the main program and the transient test program produced no surprising results. The data collected in most cases fit the theoretical predictions very well. The most significant conclusion that could be drawn from this series of tests was that for future testing of FGD systems, baseline testing may not be required, or at least can be minimized to areas where theoretical or predictive models are not well defined.

The ESP was the only portion of the Cat-Ox system that was continually operational and as a result was most thoroughly tested. The results of the tests produce the following conclusions:

- The Cat-Ox ESP can meet the design specifications.
- Low-sulfur coal reduces collection efficiency.
- The reduction in collection efficiency is not necessarily proportional to sulfur content.
- The data indicated that "soak times" required to reach steady state conditions in an ESP after a fuel change may be on the order of five days in some cases.
- A reduction in load will reduce outlet loading if all other conditions are constant and ESP had not previously reached its stopper output (i.e., if the ESP is designed for 0.005 gr/SCF or 99.6 percent efficiency and it reaches 0.005gr/SCF even if load drops, the ESP would not necessarily reduce emissions below 0.005gr/SCF).
- The effects of soot blowing on ESP performance are minimal but it does seem to decrease collection efficiency.
- Nonuniform flow does exist across the Cat-Ox ESP and can affect collection efficiency.
- The ESP collection efficiency varies with particle size. The minimum collection efficiency particle sizes between 5 and 0.05 μm seemed to be about 0.1 μm in diameter.

Other areas of the testing investigated include gaseous stratification, NO_x formation in the ESP, materials balances, and particle size versus elemental content. The details and results of the investigations are given in the test descriptions but since most of the testing was preliminary, no results are presented here.

The results of the corrosion tests are summarized in Table 83. The table shows that for the conditions experienced by the samples, corrosion resistance was generally high to very high. The major exceptions were in areas of direct contact with weak acid or condensing flue gas (points 11, B, and C). In these areas, the special alloys or lead were superior to the carbon steel (C-1008), Cortens, or alonized C-1008.

The continuous monitoring system (monitoring NO_x, SO_2, THC, O_2, CO_2, temperature, pressure, and differential pressure) operated successfully throughout the program. The automated control and integrated sampling systems developed no major problems. The only desirable element lacking in the system was a reliable continuous particle monitoring instrument.

APPENDIX A

METRIC SYSTEM CONVERSION FACTORS

Length

Units		cm	m
1 in	=	2.54	0.0254
1 ft	=	30.48	0.3048
1 yd	=	91.44	0.9144
1 mile	=	2.609344×10^5	1.609344×10^3

Area

Units		cm^2	m^2
1 in^2	=	6.4516	6.4516×10^{-4}
1 ft^2	=	929.0304	0.09290304
1 yd^2	=	8361.273	0.8361273
1 $mile^2$	=	2.589988×10^{10}	2.589988×10^6

Volume

Units		cm^3	liter
1 in^3	=	16.38706	0.01638706
1 ft^3	=	28316.85	28.31685
1 qt	=	946.353	0.946353
1 gal (U.S.)	=	3785.412	3.785412

Mass

Units		g	kg	Metric ton
1 oz (avdp)	=	28.34592	0.02834952	
1 lb (avdp)	=	453.5924	0.4535924	
1 ton	=	907184.7	907.1837	0.9071847

APPENDIX A (CONCLUDED)

Energy

Units		Btu	kWh
1 Cal (gram)	=	3.965557×10^{-3}	1.162222×10^{-6}

Temperature

Units

X degrees F = 5/9 (X - 32) degrees C

Particulate loading

Units

1 gr/CF = 2.289 gm/m^3

Corrosion rates

Units

1 cm/day = 1.437×10^5 mils per year

APPENDIX B

WOOD RIVER POWER STATION CAT-OX HISTORY

This appendix contains an internal letter from IPC with the maintenance history of the Cat-Ox process at Wood River.

March 29, 1976

P. T. Hutchison
Plant

Wood River Power Station
Cat-Ox History

Attached please find a chronological history of the Cat-Ox system, as transcribed from the Operations Department log book and other sources. The intent of this tabulation is to present, in rough form, the various events which occurred during the four (4) years since the project was begun. This is in no way a complete history, but will serve to identify the many problems which came up during operation. References are shown to allow readers to go into the original documentation if desired.

Attachment

D. E. Korneman

E

CAT-OX
CHRONOLOGICAL HISTORY
REFERENCE LIST

REF. NO.	REFERENCE SOURCE
1	Leonard Const. Co. Daily Report
2	I. P. C. Cat-Ox Operation Log
3	I. P. C. Plant Supv. Log
4	Monsanto Performance Test Report

Cat-Ox
Chronological History

Date	EVENT	REF.
3-02-71	J. S. Alberici, 1st day on job, laying out pile location.	1
3-17-71	Driving Pile.	1
1-28-72	Unit 4 started after overhaul, with Precip. in service.	3
7-20-72	Oil flush, I.D. Fan & Hydralic Coupling.	1
7-24-72	Unloading acid from car to acid storage tanks.	1
7-27-72	Operated Catalyst Handling System.	2
8-03-72	4A, 4B cooling water pumps run, system filled.	2
8-04-72	Fuel Oil System filled, checked out. Air Heater wash water checked, acid neutralization. Pit water, & drain checked out.	2 2 2
8-07-72	Air heater rotated, acid system released to IPC.	2
8-08-72	Safety showers valved in, checked. Pumped acid from storage to Absorbing Tower. Acid leak at a tower nozzle flange.	2 2 2
8-10-72	Checked rotation, Acid Recirculation Pumps. Acid leak at Absorbing Tower inlet duct flange.	2 2
8-11-72	Circulating acid through coolers & Tower Removed Recirc. Pump inlet strainers ID fan Lube Oil Pumps run, leaks observed, #4 pump rough. Pumped approx. 800 gal. acid from Abs. Tower to N. storage tank. Brick mortar repointed in Abs. Tower inlet duct, acid splash on brick noted.	2 2 2 2 2 2 2
8-16-72	Removed Cat-Ox intlet duct blanking plate.	1,2

Cat-Ox History Cont'd.

PAGE 2

DATE	EVENT	REF.
8-17-72	Transferred acid from N. storage tank to Abs. Tower Removed Cat-Ox outlet blank plate, Circulating acid through tower.	2 1,2 2
8-18-72	Operated combustion air fans on A & B reheat burners to contain flue gas leakage past dampers Operated Cat-Ox ID fan. Cat-Ox inlet damper and ID fan outlet damper frozen. Loading catalyst to converter from barrels.	2 2 2 2 2
8-19-72	ID fan on, inlet damper open 15%, outlet open 10% GHX on, burners being checked out.	2 2
8-21-72	Filling converter with catalyst. Freeing up dampers.	1,2
8-24-72	ID fan run 600 RPM for 3 hrs., resulting in condensation in Abs. Tower, strength of acid lowered from 75% to 65%.	2 2 2
8-27-72	Attempted light off of Coen burners on gas fuel failed.	2
8-28-72	Product pump used to pump dilute acid from Absorbing Tower to storage tank.	2 2
8-29-72	A & B burners test fired on gas fuel with numerous jumpers. Absorb. Tower gas inlet duct flange leaking any time acid being circulated & fan off. Unit 4 off line 2308 for R.H. or S.H. tube leak and Precipitator inspection.	2 2 2 2 2
8-30-72	Converter catalyst beds & storage bin full, acid headers drained.	2 2
9-01-72	Ran several interlock tests while Unit 4 off. Repacked Abs. Tower inlet flange, repair was quoted as being not final solution. Burner A not available. Start-up of Cat-Ox scheduled for 9-2.	2 2 2 2

Cat-Ox History Cont'd.

DATE	EVENT	REF.
9-02-72	Unit 4 on 0137. Trouble with Cat-Ox outlet damper Locked at 70% open for run. B reheat burner fired for 20 min. after many attempts. Attempted start-up discontinued until 9-03.	2 2 2 2
9-03-72	IPC Operator and MECS Start-up Eng. sprayed with acid from valve packing. Showered, no injury. No valve packing bonnet acid deflector on valve. Absorbing Tower duct leaking at rate 3 drops/sec. IP. Maint. repaired valve bonnet leak, tightened packings on Recirculation Pump & under direction of MECS broke pump packing gland. Burner B gave trouble all day.	2 All This Page Ref. 2
9-04-72	Burner "B" restarted, by 2:00 p.m. Cat-Ox up to operating temperatures, by-pass damper closed, Unit at 50 MW, stack yellow-brown, SO_2 300-400ppm.	
9-05-72	Cat-Ox on line. Burner "B" holding temperatures at 50 MW, will not hold at 88 MW. Most controls being operated manually. Approx. 8" acid transferred to storage to maintain level. Acid strength 76.5% mag. flow meter not working. Bad indication. A.C. Control Power lost accidently. Cat-Ox tripped off.	
9-06-72	Restarted Cat-Ox, ran well all day.	
9-07-72	At 2 a.m., Cat-Ox shutdown, severe leak at acid flowmeter, acid in electrical conduits, control boxes.	
9-10-72	Started Cat-Ox, by-pass closed at 11:00 p.m., 50 MW.	
9-11-72	Cat-Ox shutdown, bad acid leak at Recirc. Pump discharge header expansion joint. Joint replaced same day.	
9-12-72	Cat-Ox operated on limited rate early in day, off at 9:12 a.m., on at 4 p.m., up to operating temperatures, by 7:30 p.m., with by-pass damper closed. Unit at 100 MW.	

Cat-Ox History Cont'd.

DATE	EVENT	REF.
9-13-72	Cat-Ox on line, load reduced to 53 MW for evening, when increased to 100 in a.m. Burner B tripped off, relit satisfactory. Cat-Ox off at 7:30. Restart at 3:00 p.m., several burners on "B" not firing.	All This Page Ref. 2
9-14-72	Cat-Ox on line, B burner trips on load pickup, restarted OK. Coen still tuning burner.	
9-15-72	Burner off, Cat-Ox off 10:12 a.m. for burner work by Coen. Restart at 8:15 p.m. By-pass open 40% at 100 MW at midnight. Having trouble reaching operating temperatures.	
9-16-72	At 52 MW, by-pass closed at 2:30 a.m., temperatures nearly to design, 12 burner tips not firing. Cat-Ox tripped at 8:00 a.m., high Precip. outlet pressure on load pickup, restarted.	
9-17-72	Cat-Ox on, acid sample 77.17% at 8:30 a.m. Having to throttle product pump disch. valve to control product flow, auto-valve did not work, resulted in high pump packing leakage. By-pass damper open part way most all day with Unit at 100 MW, attempting to raise temperatures to design. 5 ft. acid in storage.	
9-18-72	Temperatures up to proper level at 00:00, 100 MW by-pass closed. At 03:00 a.m. 6'-9" acid in storage. 12 nozzels not firing in B burner. Coen man tripped fuel gas valve at 1:30 pm, relit at 4:00 p.m. At 11:00 p.m., by-pass closed, temperatures up to operating levels, acid strength decreased to 57% during time temperatures were low.	
9-19-72	At 00:25 a.m., 80 MW, temperatures normal, SO_2 at 200-240ppm. 16 B burner nozzles not firing at 04:30, acid strength at 76.3%, raising acid temperature to 280°F to increase strength to 78%. At 0645 a.m., got low level alarm on Abs. Tower, operator checked and found entire ground	

DATE	EVENT	REF.
9-19-72	area of Cat-Ox covered with acid, heavy fumes. Cat-Ox removed from service at 6:52 a.m., had to trip acid pumps from switchgear breakers, since normal stop switch was inaccessible due to acid fumes and liquid on ground. Eventually found and isolated leak on PO 4 acid recirc. pump discharge expansion joint. Approximately 2000 gal. acid spilled. Liquid caustic used to neutralize.	All This Page Ref. 2
9-20-72	Clean up and repairs. Found ID fan running without cooling water. Waste Pit Pump found with cracked casing. PO 3 and PO 4 Acid Recirc. Pumps found to be frozen, acid had corroded through bearing oil cups & allowed oil to empty, bearings also damaged. PO 4 pump motor tested and found to be shorted in motor leads from acid.	
9-21-72	Expansion joint failure inspected by vendor and MECS materials rep. Poor quality control in teflon material reported as cause for crack. Impeller of Waste Pit Pump found broken, stainless steel banding scraps found in pump thought to be the cause of failure. Splash guards designed for around expansion joints.	
9-24-72	PO 4 Acid Recirc. Pump, started, noisey, shutdown not safe to operate. PO 3 ran OK. At 1:00 a.m., Cat-Ox with by-pass closed, 75 MW. Acid recirc. flowmeter failed. Difficulty in controlling acid temperatures due to poor design of control system. Manually throttling HX inlet water valves. Unit to 100 MW @ 9:05 a.m. Coen man accidently tripped "B" burner, relit. Acid strength at 79.06%, reduced temperature to 280, strength to 77.74%. At 5:00 p.m. shut system down to repair acid leaks in pipe lines.	
10-02-72	Pumping acid to storage from Absorbing Tower. Vendor of teflon expansion joints ran tests and condemned all piping & expansion joints. All to be replaced.	

DATE	EVENT	REF.
10-06-72	Pumping acid to Absorbing Tower from storage, new teflon piping installed. Fired "B" burner at 8:30 p.m. Warming up system to 750°F maximum.	All This Page 2
10-07-72	Unit at 82 MW, by-pass closed at 1:00 p.m. Acid strength at 80.64% at 8:15 p.m., 81.11% at 10:15 p.m., unit stabilized at 10:30 p.m.	
10-08-72	Unit at 100 MW, by-pass closed. Load reduced at 2:30 a.m. to 80 MW, had to open by-pass to 10% to avoid gas flow bump and burner flameout. At 7:00 a.m., load up to 100 MW, SO_2 at stack at 170-180 ppm. Running with 1 circulation pump, two acid coolers, no flow regulation on acid side, orange-brown stack plume. A burner tried during day without success.	
10-09-72	Unit at 100 MW, Cat-Ox on line, by-pass closed. At 0100, unit load reduced to 80 MW. Acid strength 78% ± 0.5%. Noted increase in ΔP across converter from 3 to 4 in. wg. during previous 24 hours. Acid storage tank 9'-8". Cat-Ox removed from service 5:45 p.m., Unit 4 Boiler off at 7:35 p.m., due to tube leaks, in S.H. and R.H.	
10-11-72	Unit 4 on at 9:19 p.m. Acid pumps PO 3 and PO 4 started, and shutdown. PO 3 pump had leak in the discharge valve packing, PO 4 had a bad pump bearing, very noisey.	
10-12-72	Washing mist eliminators, to reduce gas pressure Δ P, resulted in weakened acid. Burner B fired at 3:00 a.m., Cat-Ox in service at 7:45 a.m. with 22 in. wg mist eliminator Pressure had trouble maintaining design gas temperatures from "B" burner.	
10-13-72	Unit at 100 MW with by-pass closed, temperatures not fully up, burner firing at maximum rate will not increase gas temperatures. At 80 MW, burner holding temperatures at design. At 3:00 a.m.,	

DATE	EVENT	REF.
10-13-72	acid at 81.3%, lowered temperature to decrease Continued washing of mist eliminator elements reduced ΔP to 16 inches. Converter pressure diff. at 6.0 inches, 10 inches is design max. I. D. fan suction at -52" at 1015 RPM, this is design maximum suction.	All Page Ref. 2
10-14-72	Burner controls testing during period midnight to 3:30 a.m. with by-pass opened.	
10-15-72	Cat-Ox partly on. burner B tripped followed by a load drop from 100 to 80 at 0015 a.m. Neither would relight. Shut Cat-Ox completely down for modification work. Work to be done. (1) install automatic acid temperature C.V. in water supply to heat exchangers, (2) change cooling water pressure control to local, manual, (3) Install air operators on acid recirc. pumps to control pressure while pump is started to protect acid coolers. (4) Modify burner gas piping, (5) Install constant voltage power supply for instruments (6) Install waste pit level alarm probes.	
10-30-72	Prepare to start up. At 5:00 p.m. B burner lighted.	
10-31-72	At midnight, converter up to 840°F, "A" burner failed to light. Tried to raise acid temperature with new water control valve, resulted in starving water flow to ID fan oil cooler. Had to return to manual throttling of acid cooler inlet valves. Burner B tripped several times, jumpers used to get relit. Acid storage tank at 12'-2-3/8" Mist eliminator washed to reduce 30" differential to 23". By-pass damper opened at 26" to reduce gas flow & diff. "B" burner tripped numerous times, was finally left off for Coen rep. due in on Nov. 1.	
11-01-72	Coen rep. attempted to start B burner, with no success. Decision made to shutdown Cat-Ox for major burner repairs & testing on oil. Acid strength raised to 78% before transferring to storage. Catalyst to be removed,	

DATE	EVENT	REF.
11-01-72	some mist eliminators to be removed, & remainder blanked to protect from oil soot while setting burners to fire fuel oil.	
11-2,3,4	Blanking plates installed on inlet & outlet, absorbing tower drained and washed down.	
11-06-72	Removing catalyst to storage trucks.	
11-15-72	All catalyst removed, Coen starting to test reheat burners on oil. Blanking plates removed.	
11-16,- 17-72	"A" burner testing. Burns oil fairly well; however, must have natural gas fire established to light oil initially, trouble with flame scanners.	
11-18	B burner testing on fuel oil. Cannot light even natural gas, trouble with pilot. Insufficient gas available from supplier to continue test. Stainless steel lining in B burner duct shows buckling.	
11-20- 11-29 11-30	Continue attempting to get burners to operate on oil with sufficient heat output and clean burning. Meeting of Coen & MECS on burner problems resulted in plans for extensive in-duct burner modifications. New equipment to be installed through winter to improve burner capability, reliability and combustion include (1) Burner nozzle combustion chambers, (2) Metered fuel, metered air combustion control system (3) Factory testing of prototype improvements, to assure MECS of design change effectiveness.	
12-01-72 2-19-73	Cat-Ox out of service, routine equipment operation to protect from corrosion, freezing, drying.	

DATE	EVENT	REF.
2-19-73	Coen and contractors in to start burner modifications, MECS people in examining Brinks mist eliminators for recommendations on further use, appear fairly dirty with oil soot. Opinion of MECS that elements should clean up satisfactorily.	All This Page Ref. 2
3-22-73	Blanking plates removed for burner checkout.	
3-23,26	Burners being tested with gas and oil, not successful in obtaining reliable operation.	
4-01-73	I. D. fan bearing temperature alarm prompted check by MECS & IPC instrument man. Alarm found to be true, fan bearings wiped, shaft scored. Cause believed to be lack of oil due to manual flow control valve being too far closed. Further checking showed a partially plugged oil cooler. The tubes in the cooler were too small for usual river water service resulting in pluggage on tube sheets. Cooling water flow & pressure available to coolers also reduced by effect of new acid temp. control valve. Blanking plates installed for ID fan work.	
5-11-73	Blanking plates removed, fan repairs complete. Added temperature thermocouples to bearings, and put temperatures on recorder in Cont. Room. Also added oil pressure switches which will trip fan on low oil pressure to bearings.	
5-12-16	Coen testing burners.	
5-16	Blanking plates installed for burner cleaning. Cleaned ID fan lube oil cooler.	
5-17	Coen cleaning burners, modifying burner controls, etc.	
5-18	Pulled blanking plates.	
5-19,20, 21	Coen test firing burners.	

Cat-Ox History Cont'd.

DATE	EVENT	REF.
5-21	IPC cleaned lube oil cooler.	2
5-22,23	Burner testing, particulate tests run by MECS, showed .017, .018 gr/SCF at outlet of B burner while firing oil, precipitator guarantee is .005.	2 2 2
5-24,25	Continued testing of burners, IPC installed blanking plates on 5-25.	2 2
5-29-	IPC started loading catalyst through sifter to converter.	2 2
5-31	Found 11 broken tubes in X-03 acid cooler. One tube previously plugged in June 1972	1,2 1,2
6-02-73	Completed refilling converter w/catalyst, short approximately 20,000 liters to fill 8th bed and for storage.	Remainder of Page Ref. 1,2
6-06-73	Mist eliminator elements being reinstalled in Abs. Tower, eight broken ceramic grid support bars are being replaced in the absorbing tower. Coen cleaning burner nozzles.	
6-09-73	Completed filling of converter with catalyst	
6-18-73	Started washing mist eliminator elements with water and Sodium, Tripoly Phosphate and Robinol X-100. Malfunction with pump and PRV. Blanking Plates removed from outlet. Larger motors installed on Burner Combustion Air Fans.	
6-19,20-73	Continued washing of Mist Eliminator; attempted to water wash gas heat exchanger, insufficient water pressure.	
6-22-73	Completed M. E. wash, transferring acid from storage to absorbing tower. Leaks observed at mag. flowmeter, tube sheet drain on Absorbing tower. Water leak on X04 acid cooler head, several inoperative pressure gauges. Due to numerous problems, acid pumped back to storage tank.	

DATE	EVENT	REF.
6-23-73	Acid leaks observed on inlet and outlet of P03 Circlating Pump, and on inlet P04 Circ. Pump, at flanges. Tube sheet drain duriron sleeve blanked off to stop acid leak. Drive pulleys on A and B Burner Combustion Air Fans replaced with original to slow speed down to within manufacturer's max recommended.	1,2 2
	MECS found several bad teflon expansion joints on Acid Cooler piping, bad welds observed on split flanges.	1,2
6-25-73	Pumping acid from storage to absorbing tower. I. D. fan started to keep flue gas in ducts, while blanking plates were being removed. High bearing temperatures caused the I.D. fan to be shutdown. Lube oil cooler was opened, found fouled and cleaned. Attempting to start up Cat-Ox system, 20 in. wg. differential across mist eliminator, could not get a burner lighted. At 7:00 p.m., Unit 4 taken off to repair S. H. tube leak.	1,2
6-27-73	Attempting start-up, using P04 pump and X03, X04 acid coolers. Many attempts to get A & B burners lighted on gas fuel. Acid leaks on acid cooler expansion joints, 3 drops per minuted. Mist eliminator differential at 20 in. with I. D. at minimum for burner off.	2
6-28-73	Low acid alarm in absorbing tower, tripped I. D. fan and B burner. Pumped more acid to tower from storage. B. burner on at 6:15 a.m. Operated with by-pass open, inlet damper to Cat-Ox at a maximum of 6% open, Mist Eliminator ΔP limited to 20 inches max. Circulation pump P02 packing leaking, switched to P03. Placed X05 acid cooler in service, X04 temperature too high.	2
6-29-73	Started washing mist eliminators with wash systems @ 125 gpm, 30 second intervals. Washing discontinued when control valve malfunctioned. Operated B burner with by pass damper open and small amount of gas	

DATE	EVENT	REF.
6-29-73	going through to assist in cleaning mist eliminators. Tried to maintain 850°F at converter and 213°F gas temperature to tower while circulating acid. Controlling acid temperature with manual valves on coolers. Topped catalyst beds off with 2 drums of catalyst.	
6-30-73	Mist eliminator washing stopped by failure of control valve. Acid being circulated with P03 pump and through X05 cooler. Working on burner controls. Repaired MEW valve, started washing ID fan at 755 rpm, M.E. at 20.8 inches pressure Maximum differential was 20 inches by design. Continued washing reduced diff. to 19.3 in. at 740 rpm.	
7-01-73	New Operating instructions from MECS start-up engineers at 9:45 a.m.; opened inlet damper to 10%, increased fan speed to 900 rpm, resulting in 28 inc. diff. on M.E., continued washing at these conditions. At 2:30 p.m., mist eliminator diff. at 29.2 in. at 910 rpm; at 11:05 p.m. M.E. diff. at 27.7 in. at 900 rpm, SO_2 in stack at 1680 ppm.	
7-02-73	During midnight shift, ID fan speed increased to obtain 30 in. diff. on M. E. Acid circulation pump P03 shut off 1:00 a.m. to repair packing leak, and P02 started. P02 pump casing broke and spilled 2" of acid from absorbing tower. System restarted at 4:00 a.m. with 29.5 in. diff. on M.E. Two more wash cycles on M. E. done during a.m. At 2:30 p.m., P04 acid pump was started and immediately failed with a hole in the pump casing. MECS reported that thermal shock was probable cause for two pump failures; P03 pump started and stopped without trouble. System shutdown at 3:25 pm with 28.9 in. diff. on M.E. at 910 rpm of ID fan.	
7-03-73	Gas heat exchanger (GHX) drive motor tripped off due to excessive seal drag. MECS had ordered ID fan shutoff before GHX was cooled down. Temperature at GHX at 580°F. GHX restarted with both air and electric	

DATE	EVENT	REF.
7-03-73	drives at 10 am and allowed to cool. IPC maintenance working on acid pumps, to isolate for further operation without leaks, pump isolation valves would not hold. During evening shift, ID fan restarted, M.E. diff. at 30 in. @ 905 rpm, SO_2 at 1800 ppm. Decided to shut system down at 11:00 pm, started cooling system down.	
7-04-73	Cooling converter down, at 6:50 am temperature to 400°F, at 6:55 am ID fan off.	
7-05-73	Installing blanking plates, pumping acid to storage. Storage at 9'9-1/2, absorbing tower at 24-1/2" before emptying. Opening manways on absorbing tower to allow removal of M.E. elements.	2
7-06-73	Washing and cleaning M.E. floor, for work inside, flushing out bed and absorbing tower.	1,2
7-07-73	Absorbing tower inspected, no support bar damage floor of inlet duct cracked and buckled. Removing HV mist eliminator elements, packing showed large amounts of black, charred soot-like material.	1,2
7-09-73	Finished removing HV M.E. elements, to be repacked at "Fabpack". Further inspection of Absorbing Tower inlet duct, insulation refractory material is soft and appears to be in poor condition.	1,2
7-10-73	Absorbing tower emptied with squegee and portable pump, there is no provision to completely drain tower. Contractors working on acid leaks and valves.	1,2
7-11-73	Began replacing H.V. mist eliminator elements.	1,2
7-12,13, 14	Installing repacked, mist eliminator elements.	1,2

Cat-Ox History Cont'd.

DATE	EVENT	REF.
7-15-73	Completed installation of M.E. elements, flanges sealed with Carbo-Kroze.	1,2
7-16-73	Removed acid pumps P02 and P04 for repair, cleaned ID fan oil cooler, repaired and replaced some M.E. tube sheet drain nozzles at lower level of Abs. Tower, used telfon sleeves inside broken Duriron sleeves. Repairing expansion joint acid leaks at acid coolers, modifying electric controls on lube oil pumps.	1,2
7-17-73	Cleaning absorbing tower closing manways. Norton Company representative in to inspect aladur bars in absorbing tower.	1,2
7-18-73	New pressure switch installed on I.D. Fan Lube Oil system for fail-safe operation on Low Lube Oil Pressure.	2
7-19-73	Blanking plates removed from inlet & outlet ducts.	2
7-20-73	Slide gates on converter catalyst inlet pipes were frozen, had to be freed up by hand before air operation would work. Pumping acid from storage to tower. Mist eliminator tube sheet drain leaking acid at sleeve into absorbing tower. Acid was pumped back to storage to allow leak to be blanked off.	2
7-21-73	Acid was pumped from storage to absorbing tower. Burners lighted on gas. At 7:00 pm started to wash S.C. section of mist eliminator with 3.2 in. pressure drop. Only one acid circulation pump available and in service.	2
7-22-73	By-pass damper closed at 70 M.W. unit load during 12-8 shift. Lost A and B burners between 8 am and 9 am. After several attempts relighted B burner at 10:00 a.m. Lost B burner again at 2:00 pm,	2

Cat-Ox History Cont'd.

DATE	EVENT	REF.
7-22-73	relighted at 5:00 pm, 5 nozzles not burning. Continued washing mist eliminator until 9:45 pm. At 10:35 pm, product acid pump in service with storage tank at 7'-11-1/2".	
7-23-73	At 6:30 am, stopped product pump. During day shift, Unit at 100 M.W., had trouble maintaining operating temperatures with B burner; also trouble lighting off. Mist eliminator diff. still high at 4.3" on S.C. section, washing helped only slight amount. At 6:45 pm, a severe electrical storm cause a trip of the Cat-Ox. Had bad acid flow indication and had to jumper interlock to allow startup, trouble lighting B burner caused by dirty flame scanners.	2
7-24-73	At 5:30 am, product acid being transferred to storage. Tank level 8'-10". Mist eliminator diff. at 8.0" on H.V. and 3.9" on S.C. at 100MW. The S.C. section was washed, but diff. did not improve.	2
7-25-73	S.C. Mist Elim. diff. increased to 4.1 inches during 12-8 shift and washing started. At 2 am, B burner lost on load drop, restarted at 2:45 am. Both A & B burners lost at 7:30 am, on unit load pickup, relit at 7:50 am. Burns on gas fuel. Shut Cat-Ox down to remove flow restriction orifice in cooling water line. Relit burners A & B at 5:30 pm. At 6:30 pm, lost A burner, relit at 6:50 pm. At 10:40 pm, lost A burner while closing by-pass damper, relit at 10:55 pm. At 10:30 began washing S.C. mist eliminator section with 4.6" diff.	2
7-26-73	Acid pumped to storage during 12-8 shift. At 6:45 am, started washing S.C. mist eliminator with 4.2 in diff. Performance test officially started at 11:00 am, with burners A & B on oil fuel.	2

DATE	EVENT	REF.
7-27-73	At 2:35 am, by-pass damper opened to reduce high Cat-Ox. Unit load reduced to 94MW and H.V. Mist Eliminators were washed 3 times. Acid strength checked at 83.5%, high due to high acid temperatures, only one acid circ. pump. At 11:30 am, B burner went out, problems relighting, two oil nozzles not firing after started. At 11:35 am, Cat-Ox tripped due to ID fan motor trip. Cause unknown. Fan on & burners relit at 1:20 pm. By-pass closed at 1:45 pm. Washing both S.C. and H.V. mist eliminators continually. Product acid at 80.6%. At 11:00pm burner B tripped off, considerable trouble relighting with even gas.	2
7-28-73	At 1:20 am, oil fire established. Continuous washing of H.V. mist eliminator to keep draft loss below trip point. Two small acid leaks reported, one at drain sleeve on absorbing tower, one in product pump. At 8:15 am., lost B burner, by-pass opened. At 9:00 am, burner on and by-pass closed. Performance test discontinued at 4:00 pm, unit to remain in service for observation. Load reduced to 72 MW to maintain acceptable draft loss.	2,4
7-29-73	Bad packing leak on product pump. At 9:00 am, transferred B burner to gas, lost fire in progress, relit on gas, 3 nozzles not firing. Continued washing H.V. and S.C. mist eliminator sections with H.V. at 9.3 in. at 5:00 pm and 13.8 in at 9:00 pm. The third acid cooler placed in service at 5:30 pm, to increase acid cooling capacity.	2
7-30-73	Having trouble maintaining acceptable acid temperatures, suspected acid cooler pluggage. Most of flue gas being by-passed to control acid temperatures. Alternately firing gas and oil to observe burner performance. By-pass damper closed when unit load reduced to 70 M.W. at 11:30 pm.	2

Cat-Ox History Cont'd.

DATE	EVENT	REF.
7-31-73	Sharp increase in acid pressure on pump discharge, indicates acid system pluggage. Pressure increased from 24 psig to 45 psig in 24 hours. Burner on gas fuel. Unable to control high acid temperatures at 100 MW with by-pass closed. Burner B outlet temperature at 680°, hence conversion rate down. Continuous mist eliminator washing. Acid strength at 81.52% at 10:00 pm, high strength result of high acid temperatures.	2
8-01-73	Bad leak on drain sleeve at absorbing tower. At 0:30 am, burner B shutdown, starting to cool unit down. Increase in absorbing tower level indicates acid cooler leak, water leaking into acid; cooling water valved out. Drained abs. tower, washing mist eliminators. Probable tube leak in X05 acid cooler.	2
8-02-73	Inlet blanking plate installed, washing of mist eliminators continued. Acid cooler X05 head removed, tube sheet plugged with remains of feroprene expansion joint cover put in absorbing tower inlet duct.	2
8-03-73	Outlet duct blanking plate installed. Acid coolers X03 and X04 opened and found to be plugged with fero-prene similar to X05, this was cause for poor acid temperature control and high acid pressures.	2
8-04-73	X03 acid cooler has four new leaks, making a total of 20 bad tubes.	2
8-06-73	Inspection of mist eliminator, absorbing tower etc.	2
8-08-73	Absorbing tower bottom cleaned. Bad teflon valve lining found on inlet to coolers.	2

DATE	EVENT	REF.
8-09-73 to 8-29-73	Misc. maintenance work being done to prepare unit for long outage to install new external burner.	2
11-01-73	All cooling water systems drained for freeze protection.	2
11-06-73	Demolition of in-duct burners started.	2
4-05-74	During outage, X03 cooler had 6 tube leaks plugged and 14 new tubes installed. Major part of External Burner construction complete. Starting equipment checkout.	2
4-08-74	Pilot gas burner lit with gas.	2
4-10-74	Gas pilot used to dry refractory in burner.	2
4-11-74	Gas fire established in main burner to dry out refractory. Temperature of 1110°F reached in burner shell.	2
4-12-74	Temperature brought up to 1500°F in burner to cure refractory. Unit 4 returned to service after overhaul.	2
4-15-74	Started testing burner on oil.	2
4-16, 17-74	Burner testing & checkout.	2
4-18-74	Burner testing, part of insulation on burner outlet duct appeared to be burning, contractor reviewing insulation specifications vs. temperatures on ducts. Sump pit pump inlet nozzle broke when pump started. Attempted to transfer acid to absorbing tower on 4-12 shift, line is plugged, could not get any flow.	
4-19-74	Found acid transfer pump base, packing gland, and rear housing corroded badly from effects of packing leak and water.	1

Cat-Ox History Cont'd.

DATE	EVENT	REF.
4-20-74	Product acid line from storage plugged with solidified. Acid and corrosion products, cutting line open and flushing out.	2
5-1-74	Product acid line washed out and dried with compressed air for 2 hrs.	
5-2-74	One leak in product line repaired and acid transferred to absorbing tower. PO3 acid circulation pump started with several acid leaks around the acid pumps.	2
5-3-74	Reheat burner fired with a small amount of flue gas passing through Cat-Ox. Found several leaking tubes in ID Fan Oil cooler when it was opened for cleaning. Catalyst levels found to be low in beds #3 and 7. Packing leak on PO4 acid pump.	2
5-4-74 5-6-74	Two tubes plugged on lube oil cooler. Acid line to product acid cooler found to be plugged and being cleaned out. Further testing on burner. Two small leaks in drain lines from mist elim.	2
5-7-74	Repairing plugged and leaking product acid lines around product pump & coolers. Acid in abs. tower checked at 59%. Leak in absorbing tower lead lining found.	1,2
5-8-74	Acid pumped to storage to repair leaks in abs. tower.	
5-9-74	Absorbing tower washed for contractor to repair leaks. Topped off #3 catalyst bed.	
5-10-74	Repair on ME drain pipes by contractor.	
5-11-74	IPC Maint. repaired catalyst elevator.	2
5-13-74	All catalyst beds topped off.	

DATE	EVENT	REF.
5-14-74	Repairs to lead lining, brickwork, and burner duct insulation by contractors continue.	Ref. 2 All This Page
5-23-74	Contractor pumping potassium silicate solution between steel shell and lead lining to stop leaks, too much pressure, heaved bottom of absorbing tower, ruptured lead lining.	
5-30-74	Additional potassium silicate pumped into space between lead and steel following internal repairs. Found one inch orifice in wrong line at acid tanks, was to have been in recirculation line, was in fill line.	
5-31-74	Pulled head off one product acid cooler, to check for plugging, found clean. Heavy rains and surface water flooded inside of acid tank impoundment, no drain provided. Water got into transfer pump motor.	
6-3-74	Blanking plates removed for start-up. Acid pumped to abs. tower from storage.	
6-4-74	Fire in burner established at 9:30 a.m., could not increase firing rate due to frozen air dampers. At 3:30 pm, dampers were operable and burner relighted. At 9:30 p.m., the "B" outlet damper was found to operate the inverse of design.	
6-5-74	At 9:00 a.m., burner lighted, warming up system. Burner shutdown later to repair leak in product acid pump.	
6-6-74	Product acid pump repaired. Absorbing tower level went up and suspect a leak in acid cooler. Product pump would not pump acid out of tower as fast as leak was admitting water, resulted in level in abs. tower increasing to point where acid ran back into inlet duct and hopper under GHX. Leak isolated to X04 cooler. A tube leak developed in the ID Fan Lube Oil cooler and the lube oil was lost into the cooling water system.	

DATE	EVENT	REF.
6-7-74	Repaired tube leaks in lube oil cooler, total of 9 now plugged.	Ref.2 All This Page
6-11-74	Inspection of ID fan & hydraulic coupling bearings. No damage was found.	
6-14-74	Installed low and high level devices on hydraulic coupling oil reservoir.	
6-17-74	Six tubes found leaking in X04 acid cooler.	
6-22-74	Acid pumped into absorbing tower from storage.	
6-24-74	Circulating with 2 pumps, ID fan started, burner lighted off & warming up of burner started. The P02 circulating pump quit pumping, P04 has a bad bearing.	
6-25-74	Acid pumped to storage for repair of acid circulating pumps. The P02 pump found to have a broken impeller. Leaks in product acid line to storage and at product pump repaired.	
6-26-74	The impeller was removed from the P04 pump and found to have cracks around the center hub.	
6-27-74	Acid circulation pump P03 also found to have cracked impeller. Causes for cracks believed to be thermal or mechanical shock. Material is very brittle, and subject to cracking. The product acid pump was disassembled and found to have severe metal wastage & corrosion on the impeller, casing, and back pump cavitation due to insufficient flow, there is no minimum flow recirculation line provided on this pump. Weak acid is also very corrosive to the pump materials.	
6-28-74	Installed blanking plates in the inlet & outlet ducts. More leaks found in the X04 acid cooler.	

DATE	EVENT	REF.
7-5-74	Seven more tubes were plugged in the X04 acid cooler.	All This Page Ref.
7-10-74	A piping change in the cooling water piping to and from the lube oil cooler was started. This will eliminate the temperature control problems with the lube oil cooler. Also incorporated in the piping changes, is a provision to allow on-stream back washing of the cooler.	
7-29-74 8-13-74	Replaced acid transfer pump casing, rear cover, and housing. Installed new casing and impeller on product pump. The P02 and P03 pumps had a new impellers installed. The P04 circ. pump was replaced with a new pump purchased from Sunoco. Two more tubes were plugged in the X04 cooler. An orificed recirculation line was installed between the product pump and the absorbing tower.	
8-14-74	Operated all 3 circulating acid pumps for checkout. Cooling water holding at 6 psi above acid pressure in coolers. Acid strength in tower at 69.65%. Blanking plates pulled. Reheat burner lighted at 8:15 pm, and starting to warm up unit.	
8-15-74	R. H. burner at 800°F all morning, acid strength lowered to 38%. Air dampers on R. H. burner binding, not allowing full firing. Shut unit down at 1:15 pm to repair acid leak in product line and free air dampers. Relighted burner at 6:15 pm, holding temperature at 1050° to dry out burner.	
8-16-74	Fire tripped accidently by Coen man at 10:50 a.m. relit at 1:00 p.m. Found leak in discharge header of acid circ. pumps, shut unit down at 5:50 pm.	
8-17-74	Blanking plates installed.	

DATE	EVENT	REF.
8-28-74	Two sections of teflon lined pipe on the circ. acid system replaced. Some refractory brick has falled from the top arch of the R.H. burner.	All Page Ref. 2
9-3-74	Ran P02 acid circ. pump, one flange leak tightened up. X04 acid cooler found to have acid tube leak.	
9-4-74	Head removed from X04 to repair leaks.	
9-9-74	Two more tubes plugged in X04, a total of 16 now plugged in the 1st pass section.	
9-13-76	Pulling tube bundle out of X04 cooler for inspection.	
9-17	Masonry contractor removing damaged brick from R.H. burner. X04 cooler tube bundle pulled out and many tubes found to be cut and gouged by inlet baffle plate and multi-pass baffles, also, serious corrosion to metal internals noted.	
10-17-74	Reassembling the X04 acid cooler. The steel shell was blast cleaned and painted with two coats of epoxy paint. Thirty-six tubes in the 1st pass section were removed and the tube sheet plugged. The inlet water baffle was relocated into the inlet pipe. Two rows of 1st pass tubes were coated with RTV at each baffle plate.	
10-19-74	The X03 acid cooler tube bundle was pulled and inspected. Its condition was worse than X04, will leave it out.	
10-25-74	Started drying out new refractory in R. H. burner with small propane burner.	

Cat-Ox History Cont'd.

DATE	EVENT	REF.
10-29/31	Continue drying new refractory. Contractor in to repair burned, and warped duct ab B transition area. Excessive expansion without adequate expansion allowance caused severe warping, tearing and buckling of S. S. duct.	All This Page Ref. 2
11-2	Completed drying of reheat burner. Work continues on new design connection at "B" transition.	
12-3-74	New steam coil hot air heater placed in service to keep moisture out of catalyst beds.	
12-10-74	Ran hydrostatic test on product acid line to storage.	
12-11.12	Flushing and drying product acid line. Relocating water inlet baffle on X05 cooler to pipe location further away from tubes.	
12-13	Completed air dry of product acid line.	
1-15-75	Steam pressure regulator valve froze and broke on R. H. burner.	
1-16-75	Removed blanks in product acid line.	
1-23-75	Test ran cooling water system to check for leaks, found OK.	
1-24-75	Test ran Cat-Ox I.D. Fan and lube oil pumps.	
1-28-75	Lighted minimum gas fire in R. H. burner to dry out and cure refractory.	
1-29	Continue drying burner with low gas fire.	
1-30-75	Completed drying out burner with gas. Raised outlet temp. to 1800°F for checkout. Started to test burner with fuel oil.	

DATE	EVENT	REF.
2-3-75	Continue checkout of burner on fuel oil, having considerable difficulty with gas pilot. Acid was transferred from storage to fill coolers, pumps and lines.	All This Page Ref 2
2-4-75	Test ran 3 acid circ. pumps with no leaks observed. Pumped part of acid back to storage. Reheat burner checkout continues, still trouble with pilots.	
2-6-75	R. H. burner checkout continues. Tube leak isolated to X04 acid cooler.	
2-7-75	R. H. burner checkout continues, pilot will now light fairly reliably. Head to be pulled on X04 acid cooler.	
2-10-75	R. H. burner fired successfully several times. Air/Oil differential control froze and ruptured.	
2-12-75	Some of the plugs in X04 tube sheet found to be weeping, drilled out and repaired.	
2-25-	Acid was transferred from storage to fill the coolers and pumps.	
2-26-	At 10:35 a fuel oil fire was established in the R.H. burner. At 1:30 pm, the P03 acid pump was started and leaks appeared in the X04 and X05 coolers. The burner was shutdown, and the acid coolers drained.	
2-27- 3-20	Continued work on plugging leaking tubes on acid coolers and testing.	
3-21-75	Acid being transferred from storage to fill coolers and lines. Acid leak at X05 cooler and at storage tank.	

DATE	EVENT	REF.
3-22-75	Acid lines and coolers filled with acid and P03 pump started. P03 pump developed an acid leak at packing and P04 pump was started. Leaks were found in both X04 and X05 coolers. Acid drained for cooler repairs.	All This Page
3-29-75	Acid transferred from storage to fill coolers, lines, and raise the level in the absorbing tower.	
3-30-75	Acid circulation pump P02 shutdown and X04 cooler drained due to additional leaks.	
4-8-75	Acid transferred from the North storage tank to the South tank. Attempted to pump acid from absorbing tower to storage, line appears plugged, no flow.	
4-9-75	Pumping acid to storage with the P04 circ. pump.	
5-12-75	The product acid line was flushed 3 hours with water and blown dry with air.	
7-14-75	The catalyst in #1 Bed was conveyed to storage in preparation for screening.	
8-7,8-75	The catalyst from #2 bed was run into #1 bed through the sifter; the #3 bed was sifted into the #2 bed.	
8-9,10,11	Catalyst was run from the #4 bed to the #3 bed through the sifter.	
8-20-75	Completed sifting of all catalyst, finished with #8 bed down approximately 10'.	
8-22	Found large quantities of catalyst between the beds in the gas spaces. This has come through the bed screens during sifting and operation. Removed approximately 100-200 bushels from these spaces.	

Cat-Ox History Cont'd.

DATE	EVENT	REF.
9-19-75	The catalyst heater was returned to service.	All This Page 2
9-22-75	The absorbing tower manways were opened and the mist eliminator wash system was operated.	
9-23-76	The upper and lower mist eliminator tube sheets were washed down. The acid trough areas were washed down.	
9-29-	Several manways were opened for	
10-03-75	Dow personnel to inspect the unit. The P02 acid circulation pump, the product pump and the transfer pump and the transfer pump were disassembled for inspection. Heater was turned off on converter.	
10-16-75	Doors on converter closed and steam heater put in service.	
10-17-75	Steam to reheat burner valved out, all cooling water systems drained for freeze protection.	

APPENDIX C

DISCRETE HARDWARE DESCRIPTION AND EVALUATION

This section evaluates the actual performance of equipment that was integrated into a complex measurement network to measure various parameters involved with the Cat-Ox process. The complexity of the measurement network derives from the fact that Cat-Ox itself is complex from the standpoint of studying the effects of individual process elements.

Equipment evaluations are intended solely as a study of the usefulness of instrumentation measurement techniques as applied to the Cat-Ox instrumentation system, and are not intended to be either positive or negative product endorsements.

Due to the large number of individual components needed to complete the instrumentation system, the components have been grouped into four areas relative to their respective uses. The four areas are: volume flow, gas analysis, data acquisition, and miscellaneous instrumentation and equipment.

Volume Flow

Volume flow measurements were needed to calculate mass flow. Volume flow can be computed by the analytical relationship of differential pressure, static pressure, temperature and duct cross-sectional area. When volume flow has been computed and gas composition determined, mass flow can be derived.

Rakes, United Sensor and Control--To conform with volume flow measurement techniques, as suggested by the ASME power test codes, and because of the large duct cross sectional areas involved, a very large number of flow sensors were required. The individual flow sensors consisted of standard type pitots for static and differential pressures, and shielded iron-constantan thermocouples for temperatures. Pitots and thermocouples were paired in close proximity to form a single sample point. Between two and seven sample points were contained on a single aerodynamic foil to produce a rake. Each location used two or more rakes in concert to represent a flow measurement location. Rakes for each particular location were identical in manufacture. For example, Point 14 (stack) had two rakes, each rake had five pairs of sensors, each pair of sensors consisted of one pitot and one thermocouple. Table C-1 shows the number of rakes at each flow measurement location and the number of sensors per rake.

Sensor pairs were positioned on their respective foils such that when all rakes for a particular flow measurement location were installed, the sensors were centered in sample areas based on the ASME power test codes. The above foils were attached to standard 6"-150# type 302 stainless steel pipe flanges. The flanges in turn were bolted to similar flanges permanently installed at appropriate flow measurement access ports.

Figure C-1 shows a typical access point.

TABLE C-1

PRESSURE AND TEMPERATURE RAKE DISTRIBUTION

MEASUREMENT LOCATION	NUMBER OF RAKES PER ASSEMBLY	NUMBER OF SAMPLE POINTS PER RAKE	TOTAL NUMBER OF SAMPLE POINTS	AREA OF MEASUREMENT LOCATION (FT^2)
1	6	5	30	509
1	8	3	24	174
3	6	3	18	136
4	4	5	20	76.5
5	6	2	12	133
8	6	3	18	310
10	4	7	28	99
14	2	5	10	452

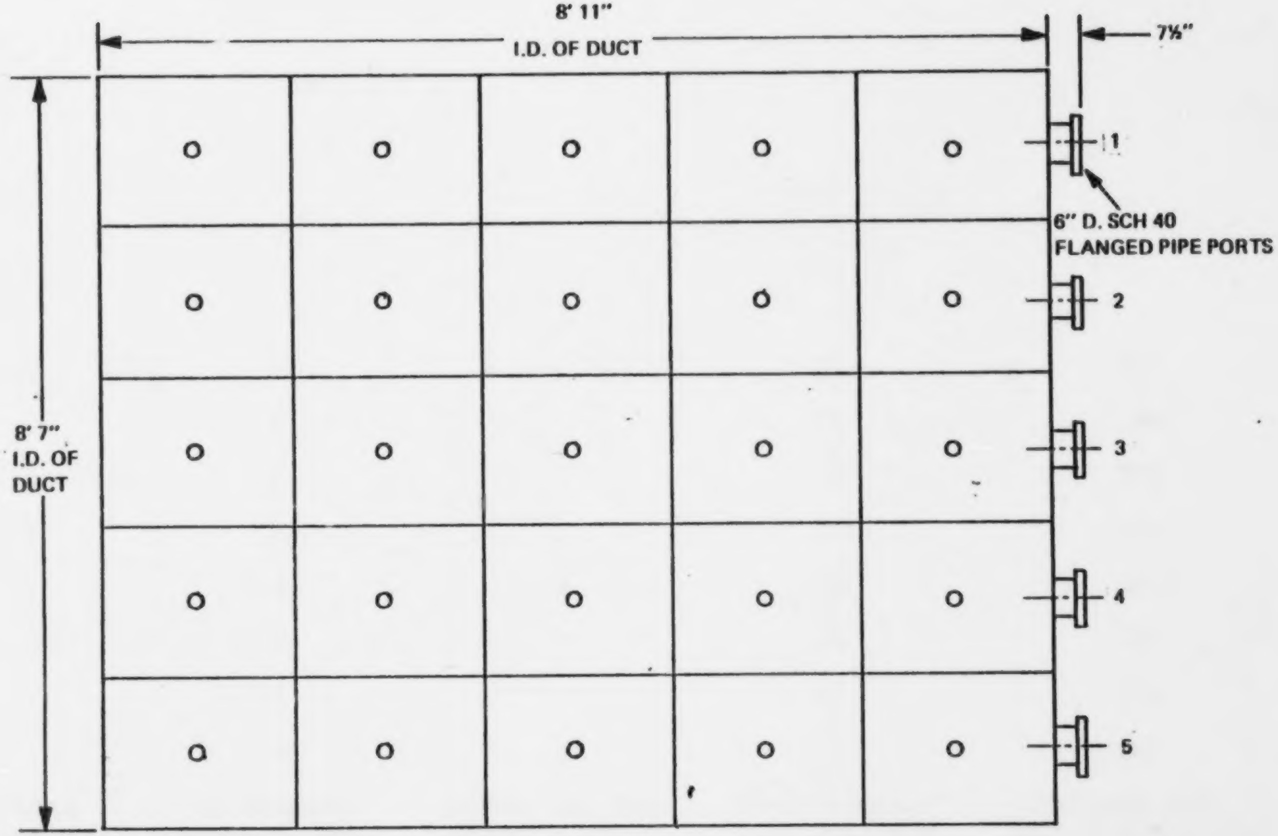
8' 11"
I.D. OF DUCT
7½"
8' 7"
I.D. OF
DUCT
1
2
3
4
5
6" D. SCH 40
FLANGED PIPE PORTS

FIGURE C-1

POINT 4—INPUT GAS HEAT EXCHANGER

With the exception of Point 1'(economizer), all rakes were self-supporting. At point 1' support hangers for each rake were located at the approximate midpoint of the duct.

Installation and removal of the rakes was straightforward when two or more persons were available; however, moderate care had to be exercised to prevent damage to the pitots as their clearance tolerances were close.

The abrasion and corrosion resistance of the rakes were very good. At point 1' (economizer) where the rakes were installed for over three years, there were no visible signs of physical degradation. Point 1, ESP input, where the flow is higher and grain loadings are of the order of 0.5 to 1 gr/SCF the probes did show signs of abrasion. The most effected area was around silver soldered joints.

All rakes were 316 stainless steel except at point 11 which was inconel. Since the unit operated only a short time, the conditions at point 11 differed from those expected and probes at that point showed some corrosion activity which blocked the static pressure ports (see Corrosion Section).

Outputs from the thermocouples were terminated in standard iron-constantan male connectors. The connectors were mounted to the back side of the rake flange. In operation all thermocouples at a particular location were connected in parallel with each other and also to an iron-constantan extension wire. The extension wire, in turn, connected the rakes to the temperature measuring system.

Without exception, the temperature measuring portion of the rakes operated superbly.

Outputs from each pitot were terminated in two 1/4 inch tube type compression fittings. One output represented the static pressure part of the pitot, the other was for differential pressure. All static pressure outputs at each location were parallel connected with 1/4 inch nylon tubing. All differential pressure outputs were connected in a similar manner. The paralleled outputs, which in effect pneumatically averaged them, were also connected to drip pots and solenoid operated air purges. The air purge was used to reverse flush all pitots, except during brief measurement periods, in order to prevent fly ash from plugging the pitots. During the measurement period, static and differential pressures were connected to appropriate transmitters.

Generally, the usability of the rakes as continuous measurement flow sensors was very good. A more desirable approach to flow measurements would be a simpler flow sensing system with fewer sampling points and large pitots, possibly S-type. The above would be, of course, dependent on the desired accuracy of flow measurements. The largest drawback to the rakes was their awkwardness caused by the bulky size coupled with cramped sampling locations.

Pressure Transmitters--

Two types of pressure transmitters were employed for the flow measurement system. They were Leeds and Northrup models 1912 and 1972 and GGS Datametrics Barocel units.

Leeds and Northrup Models 1912 and 1972--Seventeen Leeds and Northrup transmitters were used, ten for static pressures and seven for differential pressures.

The transmitters were well engineered for a power plant environment. They are ruggedly constructed and are made to stand alone in that they contain their own power supply and electronics. Documentation of the instrument, field service, and factory support and consultation services were all excellent.

The major disadvantage of the transmitter was its susceptability to drift out of desired calibration limits. To compensate for the drift of the instruments it was necessary to calibrate the transmitters on a weekly basis. Calibration required two persons; one to temporarily affix a certain known weight to the balance section of the transmitters, and a second person to monitor the results at a remote location (the instrumentation area) and inform the first person of required calibration adjustments to the instrument. This process proved to be tedious and time consuming.

If the instruments had a longer time span stability or simpler calibration procedure they would be very well suited for a continuous measurement system.

Electronic Manometers, CGS Datametrics 1023--Electronic manometers were chosen to measure the low differential pressured encountered at measurement points 1' and 14. The units are able to measure very small differential pressures. Their lower limit of sensitivity extends well below the limits encountered in a typical power plant, or would be expected from a process such as Cat-Ox.

Calibration of the units was very easily accomplished and was needed fairly infrequently (weeks between calibrations). However, because of the minimal time, calibration could be done daily with little disruption to the test. Documentation of the units and factory support and consultation services were very good.

A minor disadvantage of the Barocel units was that their sensitivity and response time was so good that minor fluctuations of differential pressures were faithfully sensed by the instruments causing "hash" on the recorders. To eliminate the "hash" for more usable records, both pneumatic and electrical damping were employed to smooth the response and output of the instruments. Pneumatic damping was accomplished by adding large sealed containers in parallel with the sensor inputs. Electrical smoothing consisted of resistor/capacitor networks on the electrical outputs of the units.

In general, the electronic manometers operated satisfactorily for the continuous measurement program.

Temperature Transmitters, Scanner--Two types of temperature transmitters were used to convert the millivolt outputs of thermocouples to a voltage convenient for recording and/or monitoring. A scanner was used so that one temperature transmitter could handle many thermocouple outputs on a time-sharing basis.

For this measurement system outputs from the up to 20 thermocouples could be connected to a junction strip in a constant temperature enclosure. The enclosure maintained equal junction temperatures such that EMFs generated by dissimilar metals would effectively cancel each other out. Copper wires from the constant temperature enclosure were connected to appropriate channel inputs of the temperature scanner. An interface circuit received information from the data acquisition system, and, in turn, controlled the temperature scanner for channel selection. The single output of the scanner was connected to the digital temperature indicator which converted the millivolt output of the thermocouples to voltages convenient for recording and/or monitoring. The output of the digital temperature indicator went to the interface circuitry, and, at the correct recording times, from there to the data acquisition system.

Temperature Transmitter, Leeds and Northrup Model #1992--To measure temperatures using iron-constantan thermocouples for the purpose of continuous recording, a transmitter is required. The transmitter does several things: First, it amplifies the millivolt output of the thermocuples to a voltage or current to a recordable level; second, it linearizes the thermocouple output; and finally, it compensates for the cold temperature junction of copper to iron and copper to constantan metal wires.

The Leeds and Northrup transmitters were factory adjusted so that their output corresponded to the ratio of 1 millivolt to a temperature of 1°F at the type J thermocouple. For example, a temperature of 650°F was converted by the transmitter to 650 millivolts (or .650 volts).

The Leeds and Northrup transmitters performed the above functions in a satisfactory manner and fitted very well into the Cat-Ox continuous measurement system.

Temperature Transmitter/Display Ircon Data Systems 3J16F--Along with performing the function of a temperature transmitter the Ircon unit also contained an integral display. The display was a digital readout which showed temperature directly in degrees Fahrenheit.

This type of transmitter/display is highly recommended for use in a continuous measurement system.

Thermocouple Scanner, Monitor Laboratories 1100--Used in conjunction with the Ircon unit, the scanner model formed an excellent mulit-point temperature measuring system. The scanner was used to select appropriate thermocouple outputs and switch those outputs to the digital temperature indicator.

A small amount of interface circuitry was needed to synchronize the temperature scanner to the data acquisition system. The interface circuitry was straightforward in design. It was designed, constructed and installed by MITRE personnel.

Gas Analysis Instrumentation--

The design goal for the gas analysis instrumentation was to incorporate continuously measuring analyzers to automatically monitor gas concentrations at several locations within, prior to, and following the Cat-Ox process. A total of seven locations were determined to be of interest for gas analysis.

Because the initial cost of gas analysis instrumentation was relatively high and multiple locations were of interest, a multi-point sequential sampler was incorporated. The sampler allowed a single set of gas analyzers to monitor a number of locations on a time sharing basis.

Sequential Sampler - Dupont Instruments--The sequential sampler was, in effect, a seven way pneumatic switch. Seven heated gas lines (Dekron lines) connected the sampler to appropriate sample points. All lines were continuously aspirated (except during blowback) by the sampler which also provided individual electrical controllers for the heated lines. Sample lines were selected by energizing a solenoid valve which in turn supplied instrument air to the appropriate piston operated ball valve. The solenoid valves could be energized either automatically by the function controller or manually by a custom built switching box.

In operation the sequential sampler proved to be a reliable and durable instrument with good documentation. Field service when needed was excellent.

SO_2NO_x Analyzer Dupont 461. Both SO_2 and NO_2 measurements were made by the Dupont 461 analyzer. Separate sample cells were used for measuring SO_2 and NO_2 gases. A source of ultraviolet radiation violet radiation and an aspirator were common to both sample cells. Spectral photometric adsorption techniques (NDUV) were used for measuring the gas concentrations.

The instrument did not measure concentrations of NO directly. The sequence used to measure NO_2 in flue gas was as follows:

1. First a sample was drawn into the NO_2 sample cell
2. The sample cell was isolated and a direct measurement of NO_2 was made.
3. Oxygen at approximately 60 PSIG was introduced into the cell.
4. NO in the sample cell was oxidized to NO_2 which was measured by the instrument.
5. After an approximate 15 minute oxidation time, the cell was flushed and the cycle restarted.

To derive the concentration of NO it was therefore necessary to mathematically substract the initial concentration of NO_2 from the total indication at the end of the oxidation cycle.

The above method for determining NO_x concentrations proved to be somewhat awkward and difficult to synchronize to the data acquisition system. A direct determination of separate NO and NO_2 concentrations would be much more desirable.

Direct determinations of concentrations of SO_2 gas were made continuously (except during blowback) by the analyzer. The SO_2 instrument operated very well and is well suited for an automatic continuous gas measuring system.

Calibration of the instrument was maintained by using certified calibration gases for spanning the analyzers and zeroing them with instrument air.

Included with the analyzers was a control station which included separate strip chart recorders for the two analyzers.

SO_2 Analyzer - Dupont 460--This instrument was similar in design to the Dupont 461 analyzer, the difference being that it analyzed only SO_2 gas concentrations.

Refer to the previous section for an evaluation and description of this instrument.

Oxygen Analyzer - Beckman Instruments Model F-3--For O_2 concentrations in flue gas, the Beckman analyzer was used. Theory of operation of the instrument involved measuring the paramagnetic effect of oxygen in a sample cell.

To protect elements of the sample cell from corrosion, water vapor was removed from the flue gas by a refrigerator-condensor.

The instrument operated very successfully as a part of the measurement system. A somewhat slow response (tens of seconds) was the only undesirable effect noted.

For calibrating the instrument, a certified gas mixture was used for spanning and pure nitrogen for zeroing.

Total Hydrocarbon Analyzer Beckman Instruments #400--Due to extremely low levels of hydrocarbons that were in the flue gas, an evaluation of the instrument is difficult to make. The instrument did appear to be capable of operating effectively in a continuous measurement system.

Operation of the instrument was based on the flame-ionization technique of measuring total hydrocarbons.

CO_2 Analyzer Bendix UNOR-6--This instrument operated very well as part of the continuous measurement system. Measurements were made by spectal photometric absorption methods (NDIR).

Water vapor was removed from the flue gas prior to the instrument to prevent a possible interference of the measurement.

A certified gas mixture was used to span the analyzer. Pure nitrogen was used to zero the analyzer.

Water Vapor Analyzer MSA LIRS M202 (modfied)--A production model MSA LIRA M202 water vapor analyzer was factory modified such that it would cover the ranges of water vapor expected in the flue gas of the Cat-Ox process. The factory modifications included two ranges of full scale measurements (0-5% or 0-15%) selectable by a front panel switch and a heated sample handling system.

The measurement method used was spectral photometric absorption (NDIR). Calibration of the instrument was accomplished by using a certified gas mixture containing ethane which has similar photometric absorption characteristics as water vapor. Pure nitrogen was used to zero the instrument.

The instrument was well made with good documentation and good field service when needed.

A problem encountered with the instrument was its susceptability to drift out of calibration. To compensate for the drift it was necesary to recalibrate the instrument, often on an hourly basis.

If the above mentioned drift problem could be corrected, the instrument would be well suited for a continuous measurement system.

Refrigerator/Condenser-Bendix--To remove water vapor from the flue gas, a refrigerator/condenser system was used. Water vapor was removed from the flue gas to prevent corrosion of the O_2 analyzer's sample cell and to prevent an interference of the CO_2 measurement. Along with the refrigerator/condenser were two pumps which maintained the correct flow and pressure of the flue gas for analysis by the O_2 and CO_2 instruments.

After extended periods of use (months) the pumps had to be rebuilt for proper operation (as could be expected). A minor modification was made to the system to protect it from over pressure that could result when the SO_2/NO_x analyzer was blowing back the sample lines.

Other than periodically rebuilding the pumps and the minor modification made to the unit, it was an excellent system.

Sample Handling System - Bendix--For the proper sample pressures and flow rates to the O_2 and CO_2 analyzers, a sample handling system was used. Included in the system were:

1. Pressure regulators to regulate the correct flue gas pressure to the analyzers.
2. Rotometers to adjust and indicate the flow rates of flue gas and calibration gases to the analyzers.
3. Solenoid valves to switch between flue gas and calibration gases to the analyzers.

The sample handling system operated without any problem for the entire time it was used in conjunction with the gas analysis instrumentation.

Data Acquisition and Associated Equipment

Electrical outputs of the analyzers and transmitter were recorded on magnetic tape for subsequent computer processing. Strip chart recorders were available for real-time monitoring of selective instruments and as backup for the magnetic tape records.

A function controller, synchronized to the data acquisition time base, was used to control certain automatic functions such as sampling point selection and blowback of the pressure measuring pitots.

TABLE D13

ELEMENTAL CONTENT OF FLUE GAS PARTICULATE MATTER

MITRE Test No. 20: 50 MW, C Fuel, No Soot Blowing, Normal Excess Air, Normal Burner Angle

	ELEMENTAL CONTENT, WEIGHT PERCENT	
ELEMENT	LOCATION 2, AIR HEATER, SAMPLE NO. 213-2*	LOCATION 3, STACK, SAMPLE NO. 213-3*
Al	9.90	9.51
Ba	0.3	0.3
Be	0.0005	0.0008
Ca	2.62	1.10
Cd	<0.0005	0.0026
Co	0.012	0.011
Cr	0.175	0.926
Cu	0.012	0.019
Fe	5.60	6.47
Ga	0.06	<0.02
Ge	0.07	0.07
Hg	0.0000	0.0003
K	3.25	2.28
Mg	0.570	0.560
Mn	0.067	0.107
Mo	0.04	0.00
Na	0.581	0.911
Ni	0.135	0.515
Pb	0.014	0.017
Sb	0.06	0.04
Se	0.05	0.005
Sn	0.1	<0.1
Sr	0.006	0.003
Ti	1.40	1.37
Tl	0.005	0.004
V	0.04	<0.04
Zn	0.08	0.16

* Midwest Research Institute's Sample Number

the analog to digital converter was processed by the coupler subelement for entry to the magnetic tape.

Data were recorded by nine track magnetic tape deck at 800 bits per inch. Each tape record consisted of twelve decimal numbers called "constant data" which were set by thumbwheel switches on the control panel, followed by 70 fields, each containing channel number (and/or sign followed by five decimal digits). These numbers were recorded in American Standard Code for Information Interchange (ASCII).

Control functions for the data acquisition system were initiated by an integral time base. The time base also supplied information to a decimal display and the magnetic tape deck for recording day of year (Julian Calender) and time of day (hours and minutes).

A teletype unit was incorporated such that a hard copy of recorded data could be obtained. This unit was also used as an input device for entering pertinent information to the magnetic tape.

As received, the data acquisition system had two minor malfunctions which prevented satisfactory operation. They were:

1. The sensing circuit for the time base was very susceptible to electrical noise which would cause erroneous time base information. The above circuit was re-engineered by MITRE personnel and subsequently operated correctly.

2. A current sinking resistor in the teletype unit was of the wrong value. The resistor was replaced by MITRE personnel which corrected false data being recorded by the teletype.

In redesigning the time sensing circuit, it was noted that individual circuit boards were constructed by questionable techniques. While the documentation was excellent, the questionable construction techniques of the circuit boards deferred expeditious troubleshooting and/or repair of the unit.

In extended operation, another more serious problem was noted with the data acquisition system. That was the susceptibility of certain switch contacts and circuit board edge connectors to corrosion. Corrosion effects would raise the nominal resistance of the contacts to a value which would derate the operability of the system substantially.

The data acquisition system was located in a partially environmentally controlled building in close proximity to the economizer section of the Unit No. 4 boiler. It was assumed that products leaking from the boiler or economizer of the No. 4 unit were responsible for the corrosion of the contacts. Therefore, it is recommended that the data acquisition system and associated equipment be located in a strictly controlled environment or that all electrical contacts be constructed of highly non-corrosive materials.

With the exception of the above mentioned problems, the data acquisition system operated very well in its role for a continuous measurement system.

Function Controller Data Graphics Corporation DGC-110-- A function controller was time synchronized with the data acquisition system. The purpose of the function controller was to activate certain remote devices (relays, solenoids, etc.) at specified times on a repeatable one hour basis. The function controller had forty timing control units (T.C.U.s) each of which was independent of the others and capable of operating several devices. Start and stop times controlled by the T.C.U.s were selected by thumbwheel switches located on the front panels of the individual units.

T.C.U.s were constructed as subassemblies which were plugged into a main frame housing. Construction and subsequent operation of the subassemblies and main frame were both excellent. Documentation of the unit was excellent.

Evidence of slight switch corrosion effects were noted, but not the degree of severity as with the data acquisition system.

Overall operation of the function controller was excellent.

Strip Chart Recorders M.F.E., M22, M23, M26-CAHA--Recorders were used in conjunction with the data acquisition system for several reasons. First, they provided a backup record source in the event that magnetic tape data were lost or invalid. Second, they were real time records that on-site personnel could use to study trends of selected instruments more easily than decommutating data from teletype or printer records. Finally, the recorders served as an aid in calibrating instruments.

M.F.E. recorders used heated stylis on a special paper to produce records. Chart speed and input ranges were switch selectable.

Switch contact corrosion was observed as mentioned in the previous two sections. The corrosion was moderate but did not impair the normal operation of the recorders.

This type of recorder is highly recommended mainly because of its flexibility in selecting chart speed and input sensitivity.

Strip Chart Recorders - Leeds and Northrup Speedomax M Mark II--

Leeds and Northrup recorders used ink pens on normal chart paper to produce records. Chart speed and full scale sensitivity were factory set leaving no latitude for field changes.

The Leeds and Northrup recorders were generally acceptable for a continuous measurement system.

Miscellaneous Instrumentation and Equipment

Included in this section is equipment not specialized to the previous major subsystems. Two major pieces of equipment have not been previously described or evaluated, those being a particle and heated gas sampling lines.

Gellman Particle Monitor--

Theory of operation of the Gellman Particle Monitor was based on beta ray absorption techniques.

Operation of the instrument was as follows:

1. A porous paper tape was positioned between a radioactive source and detector (Gieger-Mueller tube).
2. A count of beta particles via the detector and associated electronics was made to determine the absorbence of the paper tape.

3. Particles were desposited on the paper tape by isokenetically sampling the flue gas and passing the sampled stream through the paper tape which acted as a filter medium and collected the particulate matter.

4. A second count of beta particles was then made to arrive at an absorbence figure for the deposited particulate matter.

5. From the second beta particle count and by calculating the amount of flue gas sampled, particle mass per standard cubic foot of flue gas could be derived.

6. The monitor would advance the paper tape such that a fresh section of paper was in place and the operation would repeat.

The Gellman Particle Monitor resembled a laboratory instrument rather than one for on-site use for several reasons. One reason was the difficulty encountered in maintaining isokinetic sampling rates. Also, due to the temperature and moisture content of the flue gas, the paper tape tended to break often. The Geiger-Mueller tube was rather fragile and tended to break easily. Dilution of the flue gas was necessary to be in the useful measurement range of the instrument. And finally, the measuring head which was bulky, had to be located right at the desired sampling port which represented problems of supporting it and protecting it from the ambient environment.

Generally the beta-tape absorption technique appears to be a good approach to automatic particle measuring, but for this particular instrument some major equipment modifications would be required for reliable continuous measurements. As designed, the instrument could not stand the adverse effects of field operation.

Dekoron Line and Electrical Heat Controllers--Flue gas samples were conveyed to the gas analyzers by a heated teflon gas line (Dekoron line). The Dekoron line used consisted of a 3/8 inch teflon tube traced with electrical heating wires, insulated with plastic foam and sheathed with a flexible plastic tubing. Current to the heating wires was controlled by an electrical unit which used a thermistor to sense the temperature of the flue gas and automatically control the amount of current to the heating wires.

The maximum continuous lengths of Dekoron available were 100 feet. Splice kits were available to extend the length of the line but each one hundred foot section required a separate temperature controller due to voltage limitations.

Temperature differentials (ambient temperature to flue gas temperature) up to about 250°F could be maintained by the Dekoron line. This proved to be a little less than desired in cases where ambient temperature was low (mid winter).

APPENDIX D

ANALYSES OF COAL, PULVERIZER REJECTS, FURNACE BOTTOM ASH, AND FLY ASH

RESULTS OF ULTIMATE AND PROXIMATE ANALYSES

As indicated in "Baseline," Section V, ultimate and proximate analyses of pulverized coal from the coal mills were performed for each of the 21 tests in the Baseline Program. These analyses were performed both on an "as received" basis and on a "dry" basis. The analyses were performed by two separate laboratories, the Industrial Testing Laboratories (subcontractor to the Midwest Research Institute) and the Illinois Geological Survey. The results from the laboratories were then averaged as shown in Table D1 and Table D2. The first and second digit of the sample number shown on these tables and on subsequent tables correspond to the MITRE test numbers (i.e., CS 01002 corresponds to a coal sample from MITRE test number 1).

Proximate analyses were also performed on samples of fly ash removed from the dust collector and the air heater. These analyses were performed by the Industrial Testing Laboratories (subcontractor to the Midwest Research Institute) for selected tests in the program and are summarized in Tables D3 and D4.

Proximate analyses were also performed on samples of ash taken from the furnace bottom (slag samples) and from the pulverizer reject chute on the coal mills. The results of these analyses as reported

TABLE D-1

PROXIMATE AND ULTIMATE ANALYSES OF COAL

	DRY BASIS									
	PROXIMATE ANALYSES			ULTIMATE ANALYSES						
SAMPLE NUMBER	ASH	VOLATILE MATTER	FIXED CARBON	CARBON	HYDROGEN	NITROGEN	SULFUR	OXYGEN	HEATING VALUE, BTU/LB.	SOURCE OF ANALYSIS
CS01002	10.86 11.0 10.9	38.74 41.2 40.0	50.40 47.8 49.1	70.25 70.07 70.16	4.94 4.89 4.92	1.39 1.32 1.36	3.23 3.35 3.29	9.33 9.39 9.36	12,624 12,632 12,628	ITL* ISGS** AVERAGE
CS02002	10.32 10.7 10.5	37.85 40.6 39.2	51.83 48.6 50.2	71.30 70.41 70.86	4.85 4.88 4.87	1.22 1.41 1.32	3.01 2.99 3.00	9.30 9.60 9.45	12,664 12,655 12,660	ITL ISGS AVERAGE
CS03002	10.43 10.7 10.6	38.07 41.2 39.6	51.50 48.1 49.8	70.69 70.29 70.49	4.79 4.85 4.82	1.31 1.40 1.36	3.44 3.46 3.45	9.34 9.35 9.35	12,138 12,656 12,397	ITL ISGS AVERAGE
CS04002	10.82 11.1 11.0	38.45 40.0 39.2	50.74 48.9 49.8	70.79 70.15 70.47	4.92 4.86 4.89	1.36 1.39 1.38	3.48 3.55 3.52	8.63 8.93 8.78	12,630 12,546 12,588	ITL ISGS AVERAGE
CS05002	14.09 14.8 14.4	35.21 37.0 36.1	50.70 48.2 49.5	69.28 68.19 68.74	4.74 4.55 4.65	1.52 1.36 1.44	1.89 1.91 1.90	8.48 9.21 8.84	12,267 12,151 12,209	ITL ISGS AVERAGE
CS06002	11.8	40.4	47.9	70.10	4.85	1.30	2.88	9.09	12,570	ITL
CS07002	10.42 10.2 10.3	38.62 41.6 40.1	50.96 48.2 49.6	71.99 70.48 71.24	4.93 4.81 4.87	1.31 1.23 1.27	3.40 3.42 3.41	7.95 9.82 8.89	12,645 12,694 12,670	ITL ISGS AVERAGE
CS08002	10.64 10.8 10.7	38.53 40.9 39.7	50.83 48.3 49.6	71.54 69.97 70.76	4.97 4.87 4.92	1.28 1.28 1.28	3.50 3.51 3.51	8.07 9.62 8.85	12,625 12,613 12,619	ITL ISGS AVERAGE
CS09002	10.27 10.3 10.3	38.67 40.7 39.7	51.06 49.0 50.0	71.86 70.21 71.04	5.02 4.73 4.88	1.37 1.27 1.32	3.50 3.57 3.54	7.98 9.93 8.96	12,697 12,677 12,687	ITL ISGS AVERAGE
CS10002	17.26	33.04	49.70	66.46	4.42	1.48	1.71	8.67	11,719	ITL
CS11002	10.43 10.3 10.4	39.23 41.6 40.4	50.34 48.1 49.2	70.93 70.52 70.73	4.95 4.80 4.88	1.31 1.26 1.29	3.47 3.54 3.51	8.91 9.55 9.23	12,595 12,656 12,626	ITL ISGS AVERAGE
CS12002	11.15 10.8 11.0	37.79 41.3 39.5	51.06 47.9 49.5	70.22 69.92 70.07	4.84 4.83 4.84	1.30 1.26 1.28	3.31 3.41 3.36	9.18 9.77 9.48	12,500 12,588 12,544	ITL ISGS AVERAGE
CS13002	13.60 14.2 13.9	35.95 38.5 37.2	50.45 47.3 48.9	68.82 67.99 68.41	4.73 4.59 4.66	1.39 1.33 1.36	2.58 2.62 2.60	8.88 9.25 9.07	12,260 12,148 12,204	ITL ISGS AVERAGE
CS14002	11.30 11.5 11.4	37.13 40.5 38.8	51.57 48.1 49.8	70.58 70.10 70.34	4.77 4.87 4.82	1.39 1.32 1.36	2.87 2.88 2.88	9.09 9.37 9.23	12,641 12,561 12,601	ITL ISGS AVERAGE

* INDUSTRIAL TESTING LABORATORIES

** ILLINOIS STATE GEOLOGICAL SURVEY

TABLE D-1 (Concluded)

SAMPLE NUMBER	DRY BASIS									SOURCE OF ANALYSIS
	PROXIMATE ANALYSES			ULTIMATE ANALYSES						
	ASH	VOLATILE MATTER	FIXED CARBON	CARBON	HYDROGEN	NITROGEN	SULFUR	OXYGEN	HEATING VALUE, BTU/LB.	
CS15002	10.91	38.50	50.59	70.53	4.81	1.36	3.61	8.78	12,557	ITL
	10.6	41.3	48.1	70.83	4.86	1.35	3.45	8.92	12,631	ISGS
	10.8	39.9	49.3	70.68	4.83	1.36	3.53	8.85	12,594	AVERAGE
CS17002	10.58	38.95	50.47	70.58	4.83	1.17	3.57	9.27	12,637	ITL
	10.4	41.5	48.1	70.73	4.84	1.36	3.65	9.01	12,681	ISGS
	10.4	40.2	49.3	70.66	4.84	1.27	3.61	9.14	12,659	AVERAGE
CS18002	12.64	36.31	51.05	69.71	4.78	1.55	2.61	8.71	12,299	ITL
	12.7	38.8	48.5	69.49	4.62	1.40	2.73	9.05	12,347	ISGS
	12.7	37.6	49.8	69.60	4.70	1.48	2.67	8.88	12,323	AVERAGE
CS19002	9.97	39.62	50.41	71.09	4.86	1.18	3.54	9.36	12,732	ITL
	10.2	42.3	47.4	71.41	4.91	1.33	3.72	8.41	12,730	ISGS
	10.1	41.0	48.9	71.25	4.89	1.26	3.63	8.89	12,731	AVERAGE
CS20002	16.61	32.85	50.54	67.52	4.45	1.36	1.75	8.31	11,654	ITL
CS21002	9.52	56.43	34.05	71.72	4.87	1.39	3.15	9.35	12,858	ITL
	9.4	41.6	49.0	72.07	4.97	1.33	3.31	8.97	12,821	ISGS
	9.5			71.90	4.92	1.36	3.23	9.16	12,840	AVERAGE
CS22002	6.94	35.46	57.60	75.85	4.97	1.75	1.39	9.13	13,413	ITL
	6.7	37.4	55.9	76.13	4.93	1.62	1.41	9.20	13,393	ISGS
	6.8	36.4	56.8	76.00	4.95	1.69	1.40	9.17	13,403	AVERAGE

TABLE D-2

PROXIMATE AND ULTIMATE ANALYSES OF COAL

	AS RECEIVED BASIS										
	PROXIMATE ANALYSES				ULTIMATE ANALYSES						
SAMPLE NUMBER	MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	CARBON	HYDROGEN	NITROGEN	SULFUR	OXYGEN	HEATING VALUE, BTU/LB.	SOURCE OF ANALYSIS
CS01002	4.02	10.42	37.18	48.38	67.43	5.19	1.33	3.10	12.53	12,117	ITL*
	4.2	10.5	39.5	45.8	67.13	5.15	1.27	3.21	12.73	12,101	ISGS**
	4.1	10.5	38.3	47.1	67.3	5.17	1.30	3.16	12.63	12,109	AVERAGE
CS02002	4.52	9.85	36.14	49.49	68.08	5.13	1.16	2.87	12.99	12,092	ITL
	4.3	10.3	38.9	46.5	67.39	5.15	1.35	2.86	13.01	12,111	ISGS
	4.4	10.1	37.5	48.0	67.74	5.14	1.26	2.87	13.00	12,102	AVERAGE
CS03002	4.13	10.00	36.50	49.37	67.77	5.05	1.26	3.30	12.62	12,138	ITL
	4.0	10.2	39.6	46.2	67.48	5.10	1.34	3.32	12.53	12,149	ISGS
	4.1	10.1	38.1	47.8	67.63	5.08	1.30	3.31	12.58	12,144	AVERAGE
CS04002	4.31	10.35	36.79	48.55	67.74	5.19	1.30	3.33	12.09	12,086	ITL
	4.2	10.6	38.3	46.8	67.20	5.13	1.33	3.40	12.29	12,020	ISGS
	4.3	10.5	37.5	46.7	67.47	5.16	1.32	3.37	12.19	12,053	AVERAGE
CS05002	3.69	13.57	33.91	48.83	66.72	4.98	1.46	1.82	11.45	11,814	ITL
	3.6	14.3	35.7	46.4	65.73	4.79	1.31	1.84	12.08	11,713	ISGS
	3.6	13.9	34.8	47.6	66.23	4.89	1.39	1.83	11.77	11,764	AVERAGE
CS06002	4.1	11.3	38.7	45.9	67.22	5.10	1.24	2.76	12.36	12,055	ISGS
CS07002	3.89	10.01	37.12	48.98	69.19	5.17	1.26	3.27	11.10	12,153	ITL
	4.0	9.8	39.9	46.3	67.66	5.07	1.18	3.28	12.98	12,186	ISGS
	3.9	9.9	38.5	47.6	68.43	5.12	1.22	3.28	12.04	12,170	AVERAGE
CS08002	3.66	10.25	37.12	48.97	68.92	5.19	1.23	3.37	11.04	12,163	ITL
	4.0	10.3	39.3	46.4	67.17	5.12	1.22	3.37	12.79	12,109	ISGS
	3.8	10.3	38.2	47.7	68.05	5.16	1.23	3.37	11.92	12,136	AVERAGE
CS09002	3.66	9.89	37.26	49.19	69.23	5.24	1.32	3.37	10.95	12,163	ITL
	4.0	9.9	39.1	47.0	67.40	4.99	1.22	3.43	13.08	12,169	ISGS
	3.8	9.9	38.2	48.1	68.32	5.12	1.27	3.40	12.02	12,201	AVERAGE
CS10002	3.29	16.69	31.95	48.07	64.27	4.64	1.43	1.65	11.32	11,333	ITL
CS11001	3.84	10.03	37.22	48.41	68.19	5.20	1.26	3.34	11.98	12,111	ITL
	4.3	9.9	39.8	46.0	67.49	5.07	1.21	3.39	12.96	12,112	ISGS
	4.1	10.0	38.5	47.2	67.84	5.14	1.24	3.37	12.47	12,112	AVERAGE

* INDUSTRIAL TESTING LABORATORIES

** ILLINOIS STATE GEOLOGICAL SURVEY

TABLE D-2 (Concluded)

SAMPLE NUMBER	AS RECEIVED BASIS										
	MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	CARBON	HYDROGEN	NITROGEN	SULFUR	OXYGEN	HEATING VALUE, BTU/LB.	SOURCE OF ANALYSIS
CS12002	3.59	10.75	36.43	49.23	67.70	5.06	1.25	3.19	9.18	12,051	ITL
	3.9	10.4	39.7	46.0	67.19	5.07	1.22	3.28	12.85	12,097	ISGS
	3.7	10.6	38.1	47.6	67.45	5.07	1.24	3.24	11.01	12,080	AVERAGE
CS13002	3.45	13.13	34.71	48.71	66.45	4.95	1.34	2.49	11.64	11,837	ITL
	3.8	13.7	37.0	45.5	65.41	4.83	1.28	2.52	12.28	11,686	ISGS
	3.6	13.4	35.9	47.1	65.93	4.89	1.31	2.51	11.96	11,762	AVERAGE
CS14002	4.58	10.78	35.43	49.21	67.35	5.06	1.33	2.74	12.74	12,062	ITL
	4.4	11.0	38.7	45.9	67.01	5.15	1.26	2.75	12.87	12,009	ISGS
	4.5	10.9	37.1	47.6	67.18	5.11	1.30	2.74	12.91	12,034	AVERAGE
CS15002	4.30	10.44	36.84	48.42	67.50	5.08	1.30	3.45	12.23	12,017	ITL
	4.6	10.1	39.4	45.9	67.57	5.15	1.29	3.29	12.60	12,050	ISGS
	4.5	10.3	38.1	47.2	67.54	5.12	1.29	3.37	12.42	12,034	AVERAGE
CS17002	4.12	10.14	37.35	48.39	67.67	5.09	1.12	3.42	12.56	12,116	ITL
	4.4	9.9	39.7	45.9	67.62	5.11	1.30	3.49	12.52	12,123	ISGS
	4.3	10.0	38.5	47.1	67.65	5.10	1.21	3.46	12.54	12,120	AVERAGE
CS18002	3.88	12.15	34.90	49.07	67.00	5.03	1.49	2.51	11.82	11,813	ITL
	4.2	12.2	37.2	46.4	66.57	4.90	1.35	2.62	12.40	11,829	ISGS
	4.0	12.2	36.1	47.7	66.79	4.97	1.42	2.57	12.11	11,821	AVERAGE
CS19002	4.08	9.56	38.00	48.36	68.19	5.12	1.13	3.39	12.61	12,213	ITL
	4.6	9.8	40.4	45.2	68.12	5.20	1.27	3.55	12.11	12,144	ISGS
	4.3	9.7	39.2	46.8	68.16	5.16	1.20	3.47	12.36	12,179	AVERAGE
CS20002	4.04	15.94	31.53	48.50	64.80	4.72	1.30	1.68	11.56	11,184	ITL
CS21002	4.00	9.14	54.17	32.69	68.85	5.12	1.33	3.02	12.54	12,344	ITL
	4.6	8.9	39.7	46.8	68.75	5.25	1.27	3.16	12.65	12,231	ISGS
	4.3	9.1			68.80	5.19	1.30	3.09	12.60	12,288	
CS22002	4.71	6.61	33.79	54.89	72.28	5.23	1.67	1.32	12.89	12,781	ITL
	5.0	6.4	35.5	53.1	72.32	5.24	1.54	1.34	13.18	12,724	ISGS
	4.9	6.5	34.6	54.0	72.30	5.24	1.61	1.33	13.04	12,753	AVERAGE

TABLE D-3

PROXIMATE ANALYSIS OF FLY ASH FROM DUST COLLECTOR

SAMPLE NUMBER	AS RECEIVED						DRY BASIS				
	PROXIMATE ANALYSIS, %						PROXIMATE ANALYSIS, %				
	MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.
SA01004	0.16	99.61	0.78	--	0.38	20	99.77	0.78	--	0.38	20
SA03004	0.19	99.00	1.11	--	0.26	30	99.19	1.11	--	0.26	30
SA05004	0.10	99.02	0.91	--	0.30	48	99.12	0.91	--	0.30	48
SA06004	0.23	99.29	0.86	--	0.26	0	99.52	0.86	--	0.26	0
SA08004	0.11	98.62	1.86	--	0.61	91	98.77	1.86	--	0.61	91
SA10004	0.15	99.14	0.72	--	0.36	12	99.30	0.72	--	0.36	12
SA13004	0.24	97.61	1.13	1.02	0.53	80	97.84	1.13	1.02	0.53	80
SA18004	0.23	98.95	0.80	0.02	0.41	0	99.18	0.80	0.02	0.41	0
SA20004	0.16	97.46	0.29	2.09	0.30	146	97.62	0.29	2.09	0.30	146
SA21004	0.25	97.38	1.85	0.52	0.66	148	97.62	1.85	0.53	0.66	148
SA22004	0.16	97.69	0.87	1.28	0.27	167	97.85	0.87	1.28	0.27	167

TABLE D-4

PROXIMATE ANALYSIS OF AIR HEATER HOPPER ASH

SAMPLE NUMBER	AS RECEIVED						DRY BASIS				
	PROXIMATE ANALYSIS, %						PROXIMATE ANALYSIS, %				
	MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.
SA01002	0.26	98.52	1.72	--	0.52	168	98.78	1.72	--	0.52	168
SA05002	0.18	98.82	2.26	--	0.84	68	99.00	2.26	--	0.84	68
SA06002	0.12	99.21	2.12	--	0.67	46	99.33	2.12	--	0.67	46
SA08002	0.17	98.43	2.79	--	0.74	120	98.60	2.79	--	0.74	120
SA10002	0.19	97.78	2.38	--	0.39	195	97.97	2.38	--	0.39	195
SA13002	0.19	98.03	0.94	0.84	0.61	143	98.22	0.94	0.84	0.61	143
SA18002	0.20	98.17	1.10	0.53	0.39	135	98.37	1.10	0.53	0.39	135
SA21002	0.25	98.13	1.36	0.26	0.58	120	98.38	1.36	0.26	0.58	120
SA22002	0.21	97.17	1.76	0.86	0.57	271	97.37	1.76	0.87	0.57	272

by the Industrial Testing Laboratories are summarized in Table D5 and Table D6.

The results of these analyses were used to calculate a system sulfur balance and compare actual measured data against theoretical predictions (Section V).

RESULTS OF ELEMENTAL ANALYSES

Trace element concentrations were determined on four of the tests in the Baseline Program in the coal pulverizer rejects from the coal mills; bottom ash (slag); and the fly ash collected in the air heater, the mechanical collector, and locations 2 and 3. The results of these analyses are summarized in Tables D7 and D10.

Trace element concentrations were also determined for samples of fly ash collected from location 2 and location 3 for four tests in the program. The results of these analyses are summarized in Tables D11 through D15.

Additional trace elemental analyses were provided by EPA on pulverized coal for six of the test runs as summarized in Table D16.

Except for Table D16, which provides the results as parts-per-million, all results of the elemental analyses are reported in terms of weight percent. In the case of the analysis of fly ash at location 3, the results must be multiplied with the fly ash emission rate to determine emission rates to the ambient atmosphere.

TABLE D-5

PROXIMATE ANALYSIS OF SLAG SAMPLES

SAMPLE NUMBER	AS RECEIVED						DRY BASIS				
	PROXIMATE ANALYSIS, %						PROXIMATE ANALYSIS, %				
	MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.
PA01001	10.32	86.74	2.11	0.83	0.48	374	96.72	2.35	0.93	0.53	417
PA03001	34.24	63.52	1.66	0.58	0.39	241	96.60	2.52	0.88	0.59	366
PA05001	11.53	88.26	0.38	—	0.03	13	99.76	0.43	—	0.05	15
PA10001	36.85	61.74	1.19	0.22	0.12	145	97.77	1.88	0.35	0.19	230
PA21001	40.56	58.00	1.08	0.36	0.24	113	97.58	1.81	0.61	0.41	190
PA22001	35.83	63.93	0.19	0.05	0.14	16	99.62	0.30	0.08	0.22	25

TABLE D-6

PROXIMATE ANALYSIS OF PULVERIZER REJECT SAMPLES

SAMPLE NUMBER	AS RECEIVED						DRY BASIS				
	PROXIMATE ANALYSIS, %						PROXIMATE ANALYSIS, %				
	MOISTURE	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.	ASH	VOLATILE MATTER	FIXED CARBON	SULFUR	HEATING VALUE, BTU/LB.
RJ01001	0.81	54.26	20.88	24.05	26.07	4,567	54.70	21.05	24.25	26.28	4,604
RJ03001	1.28	50.93	10.45	37.34	27.61	4,994	51.59	10.59	37.82	27.97	5,059
RJ05001	3.90	33.94	26.72	15.44	16.95	8,143	35.15	27.67	15.99	17.56	8,434
RJ10001	3.40	38.94	24.51	33.15	11.27	7,521	40.31	25.37	34.32	11.67	7,786
RJ21001	0.78	53.19	15.21	30.82	20.86	4,354	53.61	15.33	31.06	21.02	4,388
RJ22001	0.54	51.11	18.48	29.87	20.68	4,794	51.39	18.58	30.03	20.79	4,820

TABLE D-7

COMPARISON OF ELEMENTAL CONCENTRATIONS IN COAL, PULVERIZER REJECTS, SLAG, AND FLY ASH (MITRE TEST NO. 1, 75 MW, B FUEL, NO SOOT BLOWING, NORMAL EXCESS AIR, NORMAL BURNER ANGLE)

	ELEMENTAL CONTENT BY WEIGHT (WEIGHT PERCENT)						
ELEMENT	PULVERIZED COAL, CS01002*	PULVERIZER REJECTS, RJ01001*	SLAG, PA01001*	FLY ASH FROM AIR HEATER ASH HOPPER, SA01002*	FLY ASH FROM MECHANICAL SEPARATOR, SA01004*	FLUE GAS PARTICULATES, LOCATION 2, AIR HEATER, DUCT, 206-2**	FLUE GAS PARTICULATES, LOCATION 3, STACK, 206-3**
Al	0.960	0.490	9.25	7.20	8.05	9.40	9.24
Ba	<0.03	<0.03	0.3	0.02	0.03	<0.04	<0.04
Be	<0.0002	<0.0002	0.0004	0.001	0.0008	0.001	0.001
Ca	0.250	1.61	3.45	4.88	1.96	2.38	0.970
Cd	0.0006	0.0004	<0.005	0.0009	0.002	0.016	0.002
Co	0.000	<0.003	0.006	0.004	0.004	0.006	0.007
Cr	0.002	0.002	0.016	0.010	0.013	0.05	0.740
Cu	0.002	0.003	0.007	0.008	0.007	0.010	0.020
Fe	0.995	13.1	16.2	14.8	10.7	11.7	11.1
Ga	0.08	<0.07	<0.02	<0.07	<0.08	<0.06	<0.06
Ge	0.0	0.0	<0.07	0.0	0.0	0.0	0.0
Hg	<0.0002	0.00006	0.0003	0.00003	0.00004	<0.00002	0.002
K	0.155	0.127	1.48	1.48	1.80	1.84	2.36
Mg	0.073	0.071	0.519	0.500	0.280	0.620	0.660
Mn	0.009	0.007	0.057	0.090	0.036	0.050	0.080
Mo	<0.002	<0.002	0.00	<0.002	0.002	<0.003	<0.003
Na	0.06	0.044	0.379	0.270	0.460	0.590	2.06
Ni	0.009	0.0009	0.013	0.010	0.040	0.05	0.200
Pb	<0.003	<0.003	0.009	0.003	<0.003	0.020	0.020
Sb	<0.07	<0.07	0.06	<0.06	<0.07	<0.06	<0.06
Se	<0.06	<0.06	<0.05	<0.06	<0.07	<0.05	<0.05
Sn	<0.05	<0.05	<0.1	<0.05	<0.05	<0.05	<0.05
Sr	<0.0005	<0.0005	0.004	0.004	0.003	0.003	<0.001
Ti	<0.098	<0.094	1.31	0.380	0.550	0.580	0.660
Tl	<0.01	0.006	0.008	0.006	<0.01	0.010	0.005
V	<0.02	<0.02	0.04	<0.02	<0.02	0.02	0.03
Zn	0.11	0.011	0.038	0.040	0.057	0.59	0.090

* MITRE SAMPLE NUMBER

** MIDWEST RESEARCH INSTITUTE SAMPLE NUMBER

TABLE D-8

COMPARISON OF ELEMENTAL CONCENTRATIONS IN COAL, PULVERIZER REJECTS, SLAG & FLY ASH (MITRE TEST NO. 3, 75 MW, A FUEL, NO SOOT BLOWING, MAXIMUM EXCESS AIR, NORMAL BURNER ANGLE)

ELEMENTAL CONTENT BY WEIGHT (WEIGHT PERCENT)				
ELEMENT	PULVERIZED COAL, CS03002*	PULVERIZER REJECT, RJ03001*	SLAG, PA03001*	FLY ASH FROM MECHANICAL SEPARATOR, SA03004
Al	0.900	0.900	8.50	8.60
Ba	<0.2	<0.2	0.3	0.3
Be	<0.0002	<0.0002	0.0004	0.0008
Ca	0.480	0.210	4.27	3.30
Cd				
Co	<0.005	0.003	0.006	0.005
Cr	0.000	0.004	0.016	0.014
Cu	0.0005	0.003	0.007	0.008
Fe	1.24	19.3	16.8	12.2
Ga	<0.05	<0.03	<0.02	<0.03
Ge	<0.07	<0.07	<0.07	<0.07
Hg	0.00000	0.00000	0.00000	0.00004
K	0.165	0.150	1.36	1.50
Mg	0.055	0.050	0.575	0.512
Mn	0.006	0.010	0.082	0.060
Mo	0.00	0.00	0.00	0.00
Na	0.073	0.080	0.400	0.650
Ni	<0.002	0.002	0.012	0.015
Pb	<0.005	0.009	0.011	0.006
Sb	<0.05	0.04	0.06	0.03
Se	<0.09	<0.05	<0.05	0.04
Sn	<0.1	<0.01	<0.1	<0.1
Sr	<0.0005	0.0005	0.008	<0.003
Ti	0.060	0.050	1.15	1.34
Tl	<0.008	0.004	0.008	0.006
V	<0.04	<0.04	<0.04	<0.04
Zn	0.009	0.427	0.032	0.044

* MITRE SAMPLE NUMBER

TABLE D-9

COMPARISON OF ELEMENTAL CONCENTRATIONS IN COAL, PYRITES, SLAG, AND FLY ASH (MITRE TEST No. 22, 75 MW, D FUEL, NO SOOT BLOWING, NORMAL EXCESS AIR, NORMAL BURNER ANGLE)

ELEMENTAL CONTENT BY WEIGHT (WEIGHT PERCENT)							
ELEMENT	PULVERIZED COAL, CS22002*	PULVERIZER REJECT, RJ22001*	SLAG, PA22001*	FLY ASH FROM AIR HEATER HOPPER, SA22002*	FLY ASH FROM MECHANICAL SEPARATOR, SA22004*	FLUE GAS PARTICULATES, LOCATION 2, AIR HEATER, 221-2**	FLUE GAS PARTICULATES, LOCATION 3, STACK, 221-3**
Al	0.600	0.500	8.40	6.40	9.50	10.0	9.50
Ba	<0.2	<0.2	0.4	0.4	<0.2	0.3	0.3
Be	<0.0002	<0.0002	0.0008	0.0006	0.001	0.001	0.002
Ca	0.250	1.28	4.55	7.90	1.78	2.09	1.33
Cd							
Co	<0.005	0.005	0.007	0.006	0.007	0.018	0.014
Cr	<0.002	0.004	0.018	0.020	0.023	0.342	0.626
Cu	0.0005	0.002	0.006	0.008	0.009	0.012	0.021
Fe	0.520	17.3	16.6	17.0	6.70	7.84	8.24
Ga	<0.05	<0.02	<0.02	<0.03	<0.03	<0.02	<0.02
Ge	<0.07	<0.07	<0.07	<0.007	<0.007	<0.07	<0.07
Hg	0.0001	0.00000	0.00000	0.00006	<0.00001	0.0004	0.0001
K	0.131	0.110	0.253	0.835	1.75	1.62	1.80
Mg	0.050	0.105	0.567	0.461	0.480	0.530	0.505
Mn	0.002	0.014	0.073	0.117	0.038	0.070	0.124
Mo	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.053	0.063	0.400	0.312	0.624	0.529	0.722
Ni	<0.002	0.001	0.010	0.013	0.026	0.165	0.390
Pb	<0.005	0.011	0.008	0.006	0.007	0.015	0.020
Sb	<0.05	0.04	0.02	0.03	0.03	0.03	0.04
Se	<0.09	0.08	<0.05	0.03	0.05	0.08	0.05
Sn	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sr	<0.0005	0.003	0.007	0.009	0.000	0.003	<0.0005
Ti	0.065	0.040	1.22	0.780	1.78	1.61	1.64
Tl	<0.008	0.006	0.008	0.004	0.004	0.01	0.008
V	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Zn	0.011	0.087	0.026	0.030	0.046	0.064	0.127

* MITRE SAMPLE NUMBER

** MIDWEST RESEARCH INSTITUTE SAMPLE NUMBER

TABLE D-10

COMPARISON OF ELEMENTAL CONCENTRATIONS IN COAL, PULVERIZER REJECTS, AND FLY ASH
(MITRE TEST NO. 5, 75 MW, C FUEL, NO SOOT BLOWING, NORMAL EXCESS
AIR, NORMAL BURNER ANGLE)

ELEMENTAL CONTENT BY WEIGHT (WEIGHT PERCENT)							
ELEMENT	PULVERIZED COAL, CS05002*	PULVERIZER REJECT, RJ05001*	SLAG, PA05001*	FLY ASH FROM AIR HEATER HOPPER, SA05002*	FLY ASH FROM MECHANICAL SEPARATOR, SA05004	FLUE GAS PARTICULATES, LOCATION 2, AIR HEATER DUCT, 211-2**	FLUE GAS PARTICULATES, LOCATION 3, STACK, 211-3**
Al		1.55	10.2	7.20	10.15	9.56	7.35
Ba		0.00	<0.04	0.3	0.4	0.5	0.3
Be		<0.0002	0.0006	0.0004	0.0006	0.0008	0.0007
Ca		0.120	5.36	7.00	3.35	3.40	1.39
Cd		0.002	0.021				
Co		<0.004	0.004	0.007	0.006	0.014	0.016
Cr		0.000	0.009	0.025	0.013	0.249	1.08
Cu		0.002	0.009	0.010	0.009	0.011	0.016
Fe		2.30	9.43	19.7	6.63	7.27	10.8
Ga		<0.06	<0.06	<0.03	<0.03	0.03	<0.06
Ge		0.0	0.00	<0.007	<0.007	<0.07	<0.07
Hg		<0.00003	0.00002	0.00000	<0.00001	0.00005	0.00008
K		0.290	2.68	0.935	1.87	1.77	1.50
Mg		0.085	0.720	0.424	0.580	0.533	0.422
Mn		0.006	0.075	0.114	0.051	0.073	0.200
Mo		<0.003	<0.002	0.00	0.00	<0.04	0.00
Na		0.10	0.635	0.370	0.220	0.991	0.750
Ni		0.004	0.031	0.010	0.017	0.239	0.600
Pb		0.007	0.009	0.010	0.007	0.018	0.014
Sb		<0.06	<0.06	0.02	0.04	0.04	<0.06
Se		<0.05	<0.05	0.05	0.02	0.060	<0.05
Sn		<0.05	<0.5	<0.1	<0.1	<0.1	<0.1
Sr		<0.001	0.009	0.006	0.009	0.004	<0.003
Ti		0.200	0.575	0.870	1.69	1.40	0.965
Tl		<0.005	0.008	0.008	0.006	0.006	0.008
V		<0.02	0.02	<0.04	<0.04	<0.04	<0.04
Zn		0.007	0.045	0.030	0.060	0.072	0.10

* MITRE SAMPLE NUMBER (OLD)

** MIDWEST RESEARCH INSTITUTE SAMPLE NUMBER

TABLE D11

ELEMENTAL CONTENT OF FLUE GAS PARTICULATE MATTER

MITRE TEST NO. 13: 35 MW, B FUEL, NO SOOT BLOWING,
NORM. EXCESS AIR, NORM. BURNER ANGLE

	ELEMENTAL CONTENT, WEIGHT PERCENT	
ELEMENT	LOCATION 2, AIR HEATER. NO. 209-2*	LOCATION 3, STACK, NO. 209-3*
Al	21.7	13.65
Ba	.008	<.04
Be	.009	.0007
Ca	1.82	.62
Cd	.0009	.001
Co	.01	.011
Cr	.15	1.68
Cu	.01	.016
Fe	8.22	8.7
Ga	<.04	<.05
Ge		
Hg		
K	2.2	1.74
Mg	.89	.51
Mn	.06	.14
Mo	.003	<.002
Na	6.29	.88
Ni	.08	.63
Pb	.03	.02
Sb	<.04	<.06
Se	<.04	<.05
Sn	<.04	<.05
Sr	.001	<.0009
Ti	.59	.50
Tl	.006	.005
V	.04	.03
Zn	.08	.11
As		
Si		

* Midwest Research Institute's Sample Number

TABLE D12

ELEMENTAL CONTENT OF FLUE GAS PARTICULATE MATTER

MITRE Test No. 8: 100 MW, A Fuel, No Soot Blowing,
Maximum Excess Air, Normal Burner Angle

ELEMENTAL CONTENT, WEIGHT PERCENT

ELEMENT	LOCATION 2, AIR HEATER, SAMPLE NO. 203-2*	LOCATION 3, STACK, SAMPLE NO. 203-3*
Al	30.9	31.8
Ba	0.4	0.6
Be	0.002	0.002
Ca	1.33	1.14
Cd	0.004	0.003
Co	0.030	0.020
Cr	0.050	0.220
Cu	0.030	0.040
Fe	14.8	11.7
Ga	0.07	<0.08
Ge	<0.09	0.00
Hg	0.0006	0.0004
K	2.54	2.42
Mg	0.770	0.670
Mn	0.090	0.080
Mo	<0.002	0.008
Na	83.6	48.6
Ni	0.05	0.09
Pb	0.110	0.160
Sb	0.170	0.130
Se	0.150	0.06
Sn	0.07	0.07
Sr	0.003	<0.0005
Ti	0.790	0.930
Tl	0.020	0.010
V	0.02	<0.02
Zn	0.060	0.080

* Midwest Research Institute's Sample Number

Temperature measurements were controlled by a subsystem consisting of a separate scanner, temperature transmitters and other associated equipment.

Data Acquisition System - Data Graphics Corporation Cat-12--

The Data Acquisition System had a basic capacity of 50 channels which was expanded, as discussed previously, with an additional twenty channels by means of a low noise temperature scanner.

The data acquisition system consisted of six main sub-elements which were: the scanner, an analog to digital converter with display, a time base with display, a coupler, a magnetic tape recorder and a teletype.

Figure 7 (Section IV) shows the overall data acquisition system.

The scanner connected the analog signal from each channel in sequence to the analog to digital converter which processed the analog signal.

Unused channels could be skipped by discrete channel override control on the front panel of the scanner. Scan rates and channel dwell times could be switch selected from the front panel also. The scanner was normally operated at one scan every two minutes with a dwell time of one second.

Outputs from the analog to digital converter were decoded to decimal digits and displayed on the front panel of the scanner. The display was used for real time system checks and for calibrating certain instruments. Binary coded decimal (BCD) information from

TABLE D14

ELEMENTAL CONTENT OF FLUE GAS PARTICULATE MATTER

MITRE Test No. 20: 50 MW, A Fuel, No Soot Blowing
MAXIMUM EXCESS Air, Normal Burner Angle

ELEMENT	ELEMENTAL CONTENT, WEIGHT PERCENT LOCATION 2, AIR HEATER, SAMPLE NO. 217-2*	LOCATION 3, STACK, SAMPLE NO. 217-3*
Al	9.00	7.75
Ba	0.3	<0.2
Be	0.001	0.001
Ca	2.80	1.17
Cd	0.0022	0.001
Co	0.008	0.013
Cr	0.125	0.725
Cu	0.010	0.020
Fe	11.9	11.4
Ga	<0.02	<0.02
Ge	<0.07	<0.07
Hg	0.0001	0.0002
K	1.54	1.42
Mg	0.470	0.430
Mn	0.049	0.149
Mo	0.00	0.00
Na	0.570	0.738
Ni	0.120	0.493
Pb	0.007	0.005
Sb	0.04	0.04
Se	0.04	0.04
Sn	<0.003	<0.003
Ti	1.25	1.21
Tl	0.008	0.006
V	<0.04	<0.04
Zn	0.066	0.088

* Midwest Research Institute's Sample Number

TABLE D15

ELEMENTAL CONTENT OF FLUE GAS PARTICULATE MATTER

MITRE Test No. 20: 50 MW, A Fuel, No Soot Blowing, Normal Excess Air, Normal Burner Angle

ELEMENT	ELEMENTAL CONTENT, WEIGHT PERCENT LOCATION 2, AIR HEATER, SAMPLE NO. 216-2*	LOCATION 3, STACK, SAMPLE NO. 216-3*
Al	8.40	5.90
Ba	<0.2	<0.2
Be	0.001	0.0008
Ca	2.57	0.660
Cd	<0.0005	<0.0012
Co	0.010	0.019
Cr	0.330	1.58
Cu	0.026	0.020
Fe	10.9	11.1
Ga	<0.02	<0.02
Ge	<0.07	<0.07
Hg	0.0001	0.0002
K	1.50	1.20
Mg	0.485	0.351
Mn	0.063	0.230
Mo	<0.04	0.00
Na	0.591	0.570
Ni	0.237	1.37
Pb	0.015	0.012
Sb	0.04	0.04
Se	0.05	0.05
Sn	<0.1	<0.1
Sr	0.005	<0.003
Ti	1.28	0.920
Tl	0.006	0.006
V	<0.04	<0.04
Zn	0.168	0.075

*Midwest Research Institute's Sample Number

TABLE D-16

ELEMENTAL ANALYSES OF COAL FOR CAT-OX BASELINE PROGRAM*
(Concentrations in ppm)

Element and Isotope / MITRE Test No.	3	5	14	18	20	22
Ag^{110}	<.7	<.6	<.2	<.6	<.9	<.2
Al^{28}	8080	13,300	10,800	12,100	17,200	6170
As^{76}	<1.2	4.8	2.44	<5	7.00	1.6
Au^{198}	.10	0.7	.06	0.15	.003	.02
Ba^{139}	34	48	45	53	92	29
Br^{80}	20	3.9	3.4	32.5	7	4.4
Br^{82}	3	22	9.0	19	20	16
Ca^{49}	3640	5640	3290	<50	7740	1910
Cd^{115}	110	110	200	<90	<300	30
Ce^{141}	8.83	16.2	10.6	13.0	21.1	8.97
Cl^{38}	1220	2760	1250	1450	2820	2350
Co^{58}	<30	<80	<60	70	<90	<30
Co^{60}	3.07	5.22	3.84	4.40	5.98	4.02
Cr^{51}	18.0	21.4	19.3	19.4	24.2	12.2
Cs^{134}	1.56	2.58	2.03	2.35	3.32	1.13
Cu^{64}	29	<20	<20	<20	<30	<20
Cu^{66}	<20	<40	<50	<20	<60	<30
Dy^{165}	0.58	0.76	0.67	0.77	1.2	0.42
Eu^{152m1}	0.2	0.32	.30	0.31	0.56	.18
Eu^{152m8}	.13	.26	.19	0.20	0.32	.12
Fe^{59}	13,700	9500	11,600	10,900	8970	4550
Ga^{72}	<2	4.0	5.5	4.2	7.2	2.9
Gd^{159}	<60	<40	<4	<30	70	<20
Ge^{75}	<4	<120	<150	<40	70	<150
Hf^{181}	.50	.81	.60	.65	1.05	.42
Hg^{203}	<.5	<.6	.16	1.91	.7	<.3
I^{128}	<1	<.05	<2	1.8	<.2	.65
In^{116}	<0.03	<0.02	0.029	.073	<0.05	<0.01
Ir^{192}	1.9	2.2	1.6	6.7	5.3	1.8

*Analyses performed by NASA Plumbrook Laboratory

TABLE D-16 (Concluded)

Element and Isotope / MITRE Test No.	3	5	14	18	20	22
K^{42}	2464	3932	3429	3748	7130	1690
La^{140}	5.7	7.2	7.3	26	17.2	5.4
Lu^{77}	.36	.42	.35	.32	.58	.22
Mg^{27}	<850	<1200	586	<4000	<450	<600
Mn^{56}	53	62	38	49	95	25
Mo^{99}	700	<260	<300	<350	<600	<200
Mo^{101}	<10	<100	<70	<40	<50	<10
Na^{24}	882	1070	757	833	1250	487
Nd^{14}	<2	<2	<7	<5	<7	<3
Ni^{65}	<50	<400	<600	<300	<1000	<200
Pt^{197}	170	<160	<200	<230	<300	<100
Rb^{86}	12.3	20.7	16.8	21.4	25.6	7.98
Rb^{88}	<550	<200	<120	<300	<300	<400
Re^{186}	<0.2	<0.2	<.4	<.3	<.3	<.3
Rh^{104}	<0.09	<0.04	<.06	<.2	<0.03	<.06
S^{37}	< 90,000	<53,000	<9060	<7000	**	<30,000
Sc^{46}	2.67	3.84	3.17	3.42	4.56	3.02
Sb^{124}	0.84	1.12	.62	.93	1.39	.86
Se^{75}	3.12	2.99	2.86	3.19	4.15	1.77
Sm^{153}	.82	1.2	1.1	1.2	2.23	0.81
Sr^{87}	<30	36	<40	<20	56	<20
Sn^{117}	<40	74.2	50	66	76.5	34
Sn^{123}	<50	<40	<15	<20	<50	<2
Sn^{125}	<200	<40	<10	<70	<500	<150
Ta^{182}	.12	.27	.18	.25	.35	.17
Tb^{160}	.018	.027	.022	.025	.036	.015
Th^{232}	2.16	3.23	2.84	2.84	4.19	1.73
Ti^{51}	912	608	908	980	1680	529
U^{23q}	0.96	0.82	0.82	1.14	1.5	0.65
V^{52}	23	26	23	27	34	15
W^{187}	<0.3	<0.4	<2	<2	<4	<2
Yb^{175}	1.88	4.06	.46	1.83	3.68	.91
Zn^{65}	<3000	220	118	148	264	<400
Zr^{95}	<50	<50	<50	<40	<50	<30

**Data missing

GASEOUS FLOW RATES

Tables D18 to D28 give the results of the gas analysis. The results in these tables were used as a basis for emissions rates described in the text as well as for the sulfur balanced calculations also discussed in "Baseline Tests," Section V.

TABLE D-17

FLOW RATES FOR SO_2 AT LOCATION 1

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	1615.9	680.2	121.4
11/11/71	12	100	A	YES*	NORM.	NORM.	1474.7	619.9	110.6
11/12/71	7	100	A	YES	NORM.	NORM.	1615.5	673.8	120.2
11/15/71	1	75	B	NO	NORM.	NORM.	1118.8	471.2	84.1
11/16/71	6	100	B	NO	NORM.	NORM.	1615.4	630.3	112.5
11/17/71	18	50	B	YES	NORM.	NORM.	679.6	282.4	50.4
11/18/71	13	35	B	NO	NORM.	NORM.	491.8	212.3	37.9
11/19/71	4	75	A	NO	MIN.	NORM.	1144.3	474.3	84.6
11/22/71	5	75	C	NO	NORM.	NORM.	196.3	81.8	14.6
11/23/71	10	100	C	YES	NORM.	NORM.	257.0	104.9	18.7
11/24/71	20	50	C	NO	NORM.	NORM.	173.9	75.1	13.4
11/30/71	2	75	A	NO	NORM.	NORM.	990.3	416.6	74.3
12/1/71	3	75	A	NO	MAX.	NORM.	1276.6	534.8	95.4
12/2/71	17	50	A	YES	NORM.	NORM.	673.7	305.9	54.6
12/3/71	19	50	A	NO	MAX.	NORM.	785.9	335.2	59.8
12/4/71	21	35	A	NO	NORM.	NORM.			
12/7/71	14	50	A	NO	NORM.	MIN.	589.3	246.7	44.0
12/8/71	15	50	A	NO	MIN.	NORM.	738.1	313.1	55.9
12/9/71	22	75	D	NO	NORM.	NORM.	404.4	160.7	28.7

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-18

FLOW RATES FOR CO_2 AT LOCATION 1

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	52,496	22,097	2,709
11/11/71	12	100	A	YES*	NORM.	NORM.			
11/12/71	7	100	A	YES	NORM.	NORM.	49,606	20,690	2,536
11/15/71	1	75	B	NO	NORM.	NORM.	32,095	13,519	1,657
11/16/71	6	100	B	NO	NORM.	NORM.	61,879	24,142	2,959
11/17/71	18	50	B	YES	NORM.	NORM.	41,805	17,374	2,130
11/18/71	13	35	B	NO	NORM.	NORM.	29,212	12,610	1,546
11/19/71	4	75	A	NO	MIN.	NORM.	44,388	18,397	2,255
11/20/71	5	75	C	NO	NORM.	NORM.	31,738	13,226	1,621
11/23/71	10	100	C	YES	NORM.	NORM.	50,692	20,695	2,537
11/24/71	20	50	C	NO	NORM.	NORM.	32,441	14,004	1,717
11/30/71	2	75	A	NO	NORM.	NORM.	58,996	24,821	3,042
12/1/71	3	75	A	NO	MAX.	NORM.	50,973	21,354	2,617
12/2/71	17	50	A	YES	NORM.	NORM.	34,738	15,771	1,933
12/3/71	19	50	A	NO	MAX.	NORM.	32,097	13,689	1,678
12/4/71	21	35	A	NO	NORM.	NORM.			
12/7/71	14	50	A	NO	NORM.	MIN.			
12/8/71	15	50	A	NO	MIN.	NORM.			
12/9/71	22	75	D	NO	NORM.	NORM.			

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-19

FLOW RATES FOR O_2 AT LOCATION 1

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	36,456	15,345	1,368
11/11/71	12	100	A	YES*	NORM.	NORM.	23,993	10,086	899
11/12/71	7	100	A	YES	NORM.	NORM.	23,683	9,878	880
11/15/71	1	75	B	NO	NORM.	NORM.	24,176	10,183	908
11/16/71	6	100	B	NO	NORM.	NORM.	34,897	13,615	1,213
11/17/71	18	50	B	YES	NORM.	NORM.	19,240	7,996	713
11/18/71	13	35	B	NO	NORM.	NORM.	19,274	8,320	742
11/19/71	4	75	A	NO	MIN.	NORM.	14,817	6,141	547
11/22/71	5	75	C	NO	NORM.	NORM.	12,806	5,337	476
11/23/71	10	100	C	YES	NORM.	NORM.	13,537	5,526	493
11/24/71	20	50	C	NO	NORM.	NORM.	11,375	4,911	438
11/30/71	2	75	A	NO	NORM.	NORM.	20,304	8,542	761
12/1/71	3	75	A	NO	MAX.	NORM.	33,311	13,955	1,244
12/2/71	17	50	A	YES	NORM.	NORM.	12,118	5,501	490
12/3/71	19	50	A	NO	MAX.	NORM.	24,573	10,480	934
12/4/71	21	35	A	NO	NORM.	NORM.			
12/7/71	14	50	A	NO	NORM.	MIN.	12,632	5,288	471
12/8/71	15	50	A	NO	MIN.	NORM.	13,178	5,589	498
12/9/71	22	75	D	NO	NORM.	NORM.	23,107	9,181	818

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-20

FLOW RATES FOR N_2 AT LOCATION 1

(NO FRACTION COUNTED AS N_2)

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	638,546	268,778	20,968
11/11/71	12	100	A	YES*	NORM.	NORM.			
11/12/71	7	100	A	YES	NORM.	NORM.	600,010	250,261	19,524
11/15/71	1	75	B	NO	NORM.	NORM.	482,031	203,034	15,839
11/16/71	6	100	B	NO	NORM.	NORM.	710,484	277,195	21,625
11/17/71	18	50	B	YES	NORM.	NORM.	334,532	139,029	10,846
11/18/71	13	35	B	NO	NORM.	NORM.	252,178	108,861	8,493
11/19/71	4	75	A	NO	MIN.	NORM.	435,611	180,539	14,084
11/22/71	5	75	C	NO	NORM.	NORM.	512,065	213,394	16,648
11/23/71	10	100	C	YES	NORM.	NORM.	598,158	244,201	19,051
11/24/71	20	50	C	NO	NORM.	NORM.	324,657	140,152	10,934
11/30/71	2	75	A	NO	NORM.	NORM.	430,498	181,120	14,130
12/1/71	3	75	A	NO	MAX.	NORM.	510,615	213,906	16,688
12/2/71	17	50	A	YES	NORM.	NORM.	275,612	125,127	9,762
12/3/71	19	50	A	NO	MAX.	NORM.	356,697	152,125	11,868
12/4/71	21	35	A	NO	NORM.	NORM.			
12/7/71	14	50	A	NO	NORM.	MIN.			
12/8/71	15	50	A	NO	MIN.	NORM.			
12/9/71	22	75	D	NO	NORM.	NORM.			

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-21

FLOW RATES FOR ALL GASES AT LOCATION 1 (SO_2, CO_2, O_2, N_2 WITH NO FRACTION COUNTED AS N_2)

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	729,113	306,900	25,166
11/11/71	12	100	A	YES*	NORM.	NORM.	646,283	271,668	21,598
11/12/71	7	100	A	YES	NORM.	NORM.	674,916	281,504	23,061
11/15/71	1	75	B	NO	NORM.	NORM.	539,421	227,207	18,488
11/16/71	6	100	B	NO	NORM.	NORM.	808,876	315,582	25,910
11/17/71	18	50	B	YES	NORM.	NORM.	396,257	164,682	13,739
11/18/71	13	35	B	NO	NORM.	NORM.	301,155	130,003	10,818
11/19/71	4	75	A	NO	MIN.	NORM.	495,961	205,551	16,971
11/22/71	5	75	C	NO	NORM.	NORM.	556,805	232,039	18,759
11/23/71	10	100	C	YES	NORM.	NORM.	662,644	270,528	22,099
11/24/71	20	50	C	NO	NORM.	NORM.	368,647	159,142	13,101
11/30/71	2	75	A	NO	NORM.	NORM.	510,788	214,900	18,008
12/1/71	3	75	A	NO	MAX.	NORM.	596,175	249,749	20,644
12/2/71	17	50	A	YES	NORM.	NORM.	323,141	146,705	12,240
12/3/71	19	50	A	NO	MAX.	NORM.	414,153	176,629	14,540
12/4/71	21	35	A	NO	NORM.	NORM.			
12/7/71	14	50	A	NO	NORM.	MIN.			
12/8/71	15	50	A	NO	MIN.	NORM.			
12/9/71	22	75	D	NO	NORM.	NORM.			

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-22

FLOW RATES FOR NO AT LOCATION 3

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	221.8	142.3	11.9
11/11/71	12	100	A	YES*	NORM.	NORM.	151.7	97.5	8.1
11/12/71	7	100	A	YES	NORM.	NORM.	149.7	94.7	7.9
11/15/71	1	75	B	NO	NORM.	NORM.	118.5	75.3	6.3
11/16/71	6	100	B	NO	NORM.	NORM.	115.0	73.3	6.1
11/17/71	18	50	B	YES	NORM.	NORM.	74.4	48.8	4.1
11/18/71	13	35	B	NO	NORM.	NORM.	55.7	37.2	3.1
11/19/71	4	75	A	NO	MIN.	NORM.	102.4	66.5	5.6
11/22/71	5	75	C	NO	NORM.	NORM.	56.6	38.0	3.2
11/23/71	10	100	C	YES	NORM.	NORM.	35.5	23.3	1.9
11/24/71	20	50	C	NO	NORM.	NORM.	26.5	18.2	1.5
11/30/71	2	75	A	NO	NORM.	NORM.	88.8	58.2	4.9
12/1/71	3	75	A	NO	MAX.	NORM.	109.5	72.5	6.1
12/2/71	17	50	A	YES	NORM.	NORM.	62.3	42.1	3.5
12/3/71	19	50	A	NO	MAX.	NORM.	84.8	57.0	4.8
12/4/71	21	35	A	NO	NORM.	NORM.	30.9	21.0	1.8
12/7/71	14	50	A	NO	NORM.	MIN.	38.8	25.2	2.1
12/8/71	15	50	A	NO	MIN.	NORM.	47.1	31.3	2.6
12/9/71	22	75	D	NO	NORM.	NORM.	57.9	36.9	3.1

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-23

FLOW RATES FOR SO_2 AT LOCATION 3

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	554.9	356.0	63.5
11/11/71	12	100	A	YES*	NORM.	NORM.	679.3	436.0	77.9
11/12/71	7	100	A	YES	NORM.	NORM.	806.8	510.2	91.0
11/15/71	1	75	B	NO	NORM.	NORM.	608.5	386.6	69.0
11/16/71	6	100	B	NO	NORM.	NORM.	765.7	488.1	87.1
11/17/71	18	50	B	YES	NORM.	NORM.	304.7	199.9	35.7
11/18/71	13	35	B	NO	NORM.	NORM.	219.6	146.8	26.2
11/19/71	4	75	A	NO	MIN.	NORM.	606.1	393.6	70.2
11/22/71	5	75	C	NO	NORM.	NORM.	167.1	112.1	20.0
11/23/71	10	100	C	YES	NORM.	NORM.	192.5	126.1	22.5
11/24/71	20	50	C	NO	NORM.	NORM.	102.0	70.1	12.5
11/30/71	2	75	A	NO	NORM.	NORM.	452.1	296.5	52.9
12/1/71	3	75	A	NO	MAX.	NORM.	586.4	388.5	69.3
12/2/71	17	50	A	YES	NORM.	NORM.	361.2	243.9	43.5
12/3/71	19	50	A	NO	MAX.	NORM.	381.1	256.2	45.7
12/4/71	21	35	A	NO	NORM.	NORM.	259.4	176.1	31.4
12/7/71	14	50	A	NO	NORM.	MIN.	341.1	221.6	39.6
12/8/71	15	50	A	NO	MIN.	NORM.			
12/9/71	22	75	D	NO	NORM.	NORM.	589.1	374.9	66.9

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-24

FLOW RATES FOR CO_2 AT LOCATION 3

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	46,737	29,281	3,675
11/11/71	12	100	A	YES*	NORM.	NORM.	47,415	30,454	3,733
11/12/71	7	100	A	YES	NORM.	NORM.	53,335	33,728	4,134
11/15/71	1	75	B	NO	NORM.	NORM.	45,041	28,611	3,507
11/16/71	6	100	B	NO	NORM.	NORM.	55,686	35,502	4,352
11/17/71	18	50	B	YES	NORM.	NORM.	27,973	18,351	2,249
11/18/71	13	35	B	NO	NORM.	NORM.	20,501	13,705	1,680
11/19/71	4	75	A	NO	MIN.	NORM.	41,380	26,869	3,293
11/22/71	5	75	C	NO	NORM.	NORM.	32,880	22,059	2,704
11/23/71	10	100	C	YES	NORM.	NORM.	47,093	30,837	3,780
11/24/71	20	50	C	NO	NORM.	NORM.	22,775	15,656	1,919
11/30/71	2	75	A	NO	NORM.	NORM.	36,375	23,856	2,924
12/1/71	3	75	A	NO	MAX.	NORM.	41,285	27,350	3,352
12/2/71	17	50	A	YES	NORM.	NORM.	24,589	16,605	2,035
12/3/71	19	50	A	NO	MAX.	NORM.	26,459	17,789	2,180
12/4/71	21	35	A	NO	NORM.	NORM.	19,297	13,102	1,606
12/7/71	14	50	A	NO	NORM.	MIN.	27,002	17,547	2,151
12/8/71	15	50	A	NO	MIN.	NORM.	25,786	17,116	2,098
12/9/71	22	75	D	NO	NORM.	NORM.	39,472	25,120	3,079

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-25

FLOW RATES FOR O_2 AT LOCATION 3

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	29,742	19,079	1,700
11/11/71	12	100	A	YES*	NORM.	NORM.	30,965	19,888	1,773
11/12/71	7	100	A	YES	NORM.	NORM.	24,720	15,632	1,393
11/15/71	1	75	B	NO	NORM.	NORM.	22,680	14,407	1,284
11/16/71	6	100	B	NO	NORM.	NORM.	27,238	17,365	1,548
11/17/71	18	50	B	YES	NORM.	NORM.	15,408	10,108	901
11/18/71	13	35	B	NO	NORM.	NORM.	13,646	9,122	813
11/19/71	4	75	A	NO	MIN.	NORM.	18,067	11,731	1,046
11/22/71	5	75	C	NO	NORM.	NORM.	8,485	5,693	507
11/23/71	10	100	C	YES	NORM.	NORM.	21,542	14,106	1,257
11/24/71	20	50	C	NO	NORM.	NORM.	12,721	8,744	779
11/30/71	2	75	A	NO	NORM.	NORM.	15,979	10,479	934
12/1/71	3	75	A	NO	MAX.	NORM.	25,256	16,731	1,491
12/2/71	17	50	A	YES	NORM.	NORM.	13,498	9,116	812
12/3/71	19	50	A	NO	MAX.	NORM.	18,059	12,142	1,082
12/4/71	21	35	A	NO	NORM.	NORM.	11,990	8,141	726
12/7/71	14	50	A	NO	NORM.	MIN.	13,501	8,773	782
12/8/71	15	50	A	NO	MIN.	NORM.	12,987	8,620	768
12/9/71	22	75	[illegible]	NO	NORM.	NORM.	16,412	10,445	931

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-26

FLOW RATES FOR N_2 AT LOCATION 3

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	347,624	222,996	17,397
11/11/71	12	100	A	YES*	NORM.	NORM.	307,852	197,725	15,425
11/12/71	7	100	A	YES	NORM.	NORM.	316,059	199,870	15,593
11/15/71	1	75	B	NO	NORM.	NORM.	250,990	159,437	12,438
11/16/71	6	100	B	NO	NORM.	NORM.	319,719	203,830	15,902
11/17/71	18	50	B	YES	NORM.	NORM.	162,228	106,427	8,303
11/18/71	13	35	B	NO	NORM.	NORM.	125,742	84,060	6,558
11/19/71	4	75	A	NO	MIN.	NORM.	231,253	150,157	11,714
11/22/71	5	75	C	NO	NORM.	NORM.	223,571	149,993	11,701
11/23/71	10	100	C	YES	NORM.	NORM.	290,170	190,009	14,823
11/24/71	20	50	C	NO	NORM.	NORM.	144,559	99,370	7,752
11/30/71	2	75	A	NO	NORM.	NORM.	206,926	135,709	10,587
12/1/71	3	75	A	NO	MAX.	NORM.	245,528	162,654	12,689
12/2/71	17	50	A	YES	NORM.	NORM.	143,898	97,177	7,581
12/3/71	19	50	A	NO	MAX.	NORM.	165,008	110,937	8,655
12/4/71	21	35	A	NO	NORM.	NORM.	122,802	83,378	6,505
12/7/71	14	50	A	NO	NORM.	MIN.	150,424	97,752	7,626
12/8/71	15	50	A	NO	MIN.	NORM.	148,038	98,260	7,666
12/9/71	22	75	D	NO	NORM.	NORM.	233,098	148,345	11,573

* REDUCED LEVEL OF SOOT BLOWING

TABLE D-27

FLOW RATES FOR ALL GASES AT LOCATION 3
(NO, SO_2, CO_2, O_2, & N_2)

DATE	MITRE TEST NUMBER	TEST CONDITIONS					VOLUME FLOW (ACTUAL FT^3 PER MIN.)	VOLUME FLOW (STANDARD FT^3 PER MIN.)	MASS FLOW (LB. PER MIN.)
		LOAD FACTOR	FUEL TYPE	SOOT BLOWER	EXCESS AIR	BURNER ANGLE			
11/8/71	11	100	A	NO	NORM.	NORM.			
11/9/71	9	100	A	NO	MIN.	NORM.			
11/10/71	8	100	A	NO	MAX.	NORM.	424,879	272,554	22,848
11/11/71	12	100	A	YES*	NORM.	NORM.	387,063	348,601	21,017
11/12/71	7	100	A	YES	NORM.	NORM.	395,070	249,835	21,219
11/15/71	1	75	B	NO	NORM.	NORM.	319,438	202,917	17,305
11/16/71	6	100	B	NO	NORM.	NORM.	403,524	257,258	21,894
11/17/71	18	50	B	YES	NORM.	NORM.	205,988	135,135	11,493
11/18/71	13	35	B	NO	NORM.	NORM.	160,163	107,071	9,080
11/19/71	4	75	A	NO	MIN.	NORM.	291,409	189,217	16,129
11/22/71	5	75	C	NO	NORM.	NORM.	265,160	177,894	14,936
11/23/71	10	100	C	YES	NORM.	NORM.	359,034	235,102	19,885
11/24/71	20	50	C	NO	NORM.	NORM.	180,184	123,858	10,465
11/30/71	2	75	A	NO	NORM.	NORM.	259,821	170,399	14,503
12/1/71	3	75	A	NO	MAX.	NORM.	312,764	207,196	17,608
12/2/71	17	50	A	YES	NORM.	NORM.	182,408	123,184	10,476
12/3/71	19	50	A	NO	MAX.	NORM.	209,992	141,181	11,968
12/4/71	21	35	A	NO	NORM.	NORM.	154,380	104,818	8,869
12/7/71	14	50	A	NO	NORM.	MIN.	191,306	124,319	10,600
12/8/71	15	50	A	NO	MIN.	NORM.	186,857	124,027	10,534
12/9/71	22	75	D	NO	NORM.	NORM.	289,629	184,322	15,653

* REDUCED LEVEL OF SOOT BLOWING

APPENDIX E

ENVIRONMENT AT TEST LOCATIONS

This Appendix contains the test location environment records and the physical descriptions of the sample coupons before and after each test. The location environment section gives a brief description of the actual conditions at the specific test locations for each test. These descriptions are significantly different in most cases from those expected when the system is operating (Table 76 of the text). The physical appearance of the coupons is given to aid those interested in corrosion but requiring more data than the weight loss data given in the text. The appearance is described by coupon number and the actual material is given in Table 75, elemental content of test specimens.

Conditions at Location "B" (Recirculating Acid to Product Cooler)

After initial attempts to start Cat-Ox in August 1974 failed, the acid was stored in the absorbing tower instead of being transferred to the storage tanks. As a result, these coupons were immersed in an acid whose strength varied between 65 and 50 percent.

The corrosion rack at this location is placed within a specially designed valve which allows the rack to be removed while acid is in the lines. Illinois Power Company personnel attempted to operate the valve with the corrosion rack still in pace resulting in some minor damage to a number of the coupons. Though this reduces the sensitivity of the analysis, the information gained here was quite useful and is felt adequate to produce reliable results.

Since coupons of 5 and 6 were totally destroyed in only a three month period, these samples were rejected. Similarly, the corrosion rate for number 4 was two orders of magnitude higher than the other metals; hence, it, too was rejected for this type of application. Table E-1 describes the physical appearance of coupons taken out of Point "B".

Conditions at Location "C" (Acid From Product Cooler)

Coupons in this area are exposed to acid when the acid product pump is run. During this test period, the pump was operated very little and hence the direct exposure to H_2SO_4 was minimal. Coupons which indicate significant corrosion will be rejected to make room for new samples due to the space limitations in this area. Table E-2 describes the sample conditions.

Conditions at Point 3 (Output of ESP)

The coupons in this location were exposed to flue gas at about 320°F. Particulate loading in this area ranged between 0.02 to 0.004 grains/SCF. These samples were removed for about 15 to 30 minutes a day during the ESP tests in September, but except for this they remained in the flue gas stream continuously. Table E-3 presents a physical description of each coupon after exposure. Conditions should be the same with Cat-Ox on-line.

TABLE E1

First Period

DESCRIPTION OF SAMPLES ON REMOVAL FROM LOCATION "B"

Coupon No.	Initial Appearance	Appearance After Washing
1	Clean surface	*No corrosion visible
2	Clean surface	No corrosion visible
3	Clean surface	*No corrosion visible
4	Surface covered with green-blue deposits and rust	Rust colored, excessive visible corrosion
5	Destroyed	
6	Destroyed	
7	Clean surface	*No corrosion visible
16	Clean surface	*No corrosion visible
14	(Sample added 2/11/75 to Replace 5, 6, and 4)	
12	(Sample added 2/11/75 to Replace 5, 6, and 4)	
15	(Sample added 2/11/75 to Replace 5, 6, and 4)	

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*Damaged by value

**Samples 4, 5, and 6 were rejected

TABLE E2

DESCRIPTION OF SAMPLES ON REMOVAL FROM LOCATION "C"

Coupon No.	Initial Appearance	Appearance After Washing
1	Clean, No corrosion	Minor tarnished area in one corner
2	Clean, No corrosion	No corrosion
3	Clean, No corrosion	No corrosion
4	Sulfate covered	Pitted and extensive corrosion
5	Sulfate covered	Pitted and extensive corrosion
6	Sulfate covered	Pitted and extensive corrosion
7	Clean, No corrosion	No corrosion
9	Sulfate covered	Pitted and extensive corrosion
10	Clean	Surface rough on one side
11	Clean, No corrosion	No corrosion
12	Covered with crystalline	Deposits of Cu on surface
13	Clean, No corrosion	No corrosion
14	New	
15	New	
16	New	

TABLE E3

DESCRIPTION OF SAMPLES AT POINT 3

Coupon No.	Initial Appearance	Appearance After Cleaning
1	Covered with fly ash	Dull steel color, no noticeable corrosion
2	Covered with fly ash	Dull steel color, no noticeable corrosion
3	Covered with fly ash	Dull steel color, no noticeable corrosion
4	Covered with fly ash	Reddish black oxide surface
5	Covered with fly ash	Reddish black oxide surface
6	Covered with fly ash	Black surface, no rust
7	Covered with fly ash	Dark grey color
9	Covered with fly ash	Metallic gray color

Conditions at Point 4 (Input to Heat Exchanger)

These samples have been exposed to ambient conditions during most of this test period. During the attempted Cat-Ox start-up in August of 74, the samples were exposed to flue gas and temperatures exceeding 200°F for a period less than two full days. The physical description of the coupons is given in Table E4.

Conditions at Point 5 (Input to Converter)

The conditions at this point were ambient for most of the test period. However, for about five days this location was exposed to flue gas and temperatures between 200°F and 800°F. See Table E5 for a physical description of samples.

Conditions at Location 8

These coupons were not checked prior to the first corrosion report. The conditions over the first test period were generally ambient except for about a one week period when temperatures were as high as 800°F for a short period of time. During this short period the atmosphere was a dilution of flue gas. Table E6 describes the coupon appearance.

Conditions at Point 10 (Input to Absorbing Tower)

Under normal conditions these coupons would be in an ambient atmosphere when Cat-Ox is not operational. After the last start-up attempt, the acid was stored in the base of the absorbing tower which is directly connected to Point 10. As a result the coupons were exposed to acid gas during this test period. Temperature was at

TABLE E4

DESCRIPTION OF SAMPLES AT POINT 4

Coupon No.	Initial Appearance	Appearance After Cleaning
1	Coupon was covered with a thin layer of white and rust colored deposits	Surface showed minor pitting over entire coupon, most prevalent near mounting hole
2	Covered with a thin layer of rust colored deposits; surface had a greenish-yellow color in one spot on the front and back	No significant corrosion; visible surface was normal
3	Rust deposits on one edge; also greenish-yellow material on one edge	Surface showed minor pitting over entire coupon, most prevalent near mounting hole
4	Dark and light rust colored oxide layer surface; yellow deposit on one corner	Rust over entire surface; back surface slightly smoother
5	Covered with rust colored oxide layer with yellow deposit on one corner	Rust over entire surface except for two areas covered by yellow deposit where little or no oxidizing took place
6	Covered with rust colored oxide layer with yellow deposit in top corner	Rust over entire surface except for two areas covered by yellow deposit where little or no oxidizing took place
7	Some rust colored deposits on outside but no layer of any material	Dark gray except bottom back area, which is light gray

TABLE E4

DESCRIPTION OF SAMPLES AT POINT 4 (CONCLUDED)

Coupon No.	Initial Appearance	Appearance After Cleaning
8	Light colored layer of rust	Surface evenly rusted
9	Light colored layer of rust, but more flakey or layered than No. 8	Center shows less oxide than rest of sample; no I.D. No. visible

*Note: When the term rust deposit is used, it implies that the rust was from some external metal and collected on the coupon.

TABLE E5

DESCRIPTION OF SAMPLES FROM POINT 5

FIRST PERIOD

Coupon No.	Initial Appearance	Appearance After Washing
1	Deposits of granular material, burned tarnished color	Tarnished as material that has been hot
2	Spots of rust on outer edges	Same burned tarnished color rust spots
3	Spots of rust on outer edges	Tarnished as material that has been hot
4	Tenuous layer of oxide	Black or dark color
5	Tenuous layer of oxide	Rough surface, black or dark rust color
6	Tenuous layer of oxide	Dark rust and black color

TABLE E6

DESCRIPTION OF COUPONS AT POINT 8

FIRST PERIOD

	Appearance Before Washing	Appearance After Washing
1	Tarnished surface with some orange-brown green deposits (spots)	Tarnished or burned in some areas, stains where deposits were
2	Small rust pits and spots of brown and yellow deposits (pits near edge)	Pitted areas and some tarnish, or spots at deposits
3	Similar to #1 less deposits	Same as #1 (blue-black tarnish)
4	Surface covered with rust and deposits	Dark rust color
5	Surface covered with rust and deposits	Dark rust color one side shows roll grains due to rusting in localized boundaries.
6	Surface covered with rust and deposits not as heavy in center	Black metal and rust (heaviest near edges)
8	Surface covered with rust and deposits	Black metal and rust (heaviest near edges)
9	Same as #4 but not as heavy rust only in spots	Small pits and rust not heavy
10	Deposits on surface mostly yellow and white some rust deposit	Similar to #2
11	Same as #3	Same stain from deposits
12	Heaviest deposits evenly cover surface light green and white some rustic color	No noticeable corrosion
13	Less deposits than others	No noticeable corrosion

ambient for most of the test period. Table E7 describes the coupons after removal from the test location.

Conditions at Point 11 (Output From Mist Eliminator)

During operational conditions, this area is exposed to the flue gas after it passes the mist eliminator. When Cat-Ox is not operating, the area is by-passed by direct flow. Though the flue gas does not flow through Point 11 when the by-pass is open some of the gas will circulate into this stagnant area as a result of turbulance and normal mixing of gases. This area is at ambient temperature and therefore, the corrosive gas condenses on the coupons. See Table E8 for physical description.

Conditions at Point 13 (Input to Stack)

Point 13 was similar to Point 3 except the temperature was about 250°F. Table E9 gives the physical description of the samples.

C.2 Environment at Test Locations During 2nd Test Period

Conditions at Location "3"

The coupons at Location 3 were exposed to flue gas at 320°F. The particulate loading in this area is about 0.02-0.004 gr/scf. The coupons where in this atmosphere continuously except during Unit No. 4 down times or when they were removed during a particulate test (30 days total time). Table E10 gives the sample appearance on removal of the rack.

Conditions at Location "4"

These coupons have been exposed to ambient conditions over most of this period of the test period. The only exception was

TABLE E7

DESCRIPTION OF SAMPLES AT POINT 10

Coupon No.	Initial Appearance	Appearance After Cleaning
1	Covered with layer of yellow material	One region in upper right was discolored (dull), much of surface appears grainy (silvery & shiny regions) apparently small pits, most frequent 1/8" from mounting hole
2	Blue yellow material on surface	A number of discolored or dull regions, no significant corrosion, surface smooth
3	Yellowish green material on surface	Same grainy surface (small pits) as number 1
4	White and yellow material on surface	Tarnished color (rust and black and blue color) no visible corrosion
5	White & yellow material on surface	Tarnished color (rust and black and blue color) no visible corrosion
6	Surface cover with white and gray material	Tarnished and surface deformation over most of sample, showed less corrosion where tenuous white material was
7	Surface white and gray and black	Black and dark gray color, minor pitting
8	White coating, black underneath	Tarnished and rough
9	White coating, one area approximately 1/2" thick	One spot rusted, significant corrosion in area where large buildup was, also some pitting

TABLE E8

DESCRIPTION OF SAMPLES AT POINT 11

Coupon No.	Initial Appearance	Appearance After Cleaning
1	Covered with loose granular black and brown material	Extensive pitting generally smaller than 1/64"
2	Covered with loose granular black and brown material	Extensive pitting, some exceeding 1/64" in depth approximately 3 to 4 1/64" per 1/4 x 1/4" area
3	Covered with loose granular black and material	Pitting smaller and less than number 1
4	Loose flakey layer of rust chips off in large flakes	Rough surface evenly oxidized
5	Loose flakey layer of rust chips off in large flakes	Rough surface evenly oxidized
6	Loose flakey layer of rust chips off in large flakes but some areas of outer rust layer are tenuous (remain stuck to surface)	Rough surface evenly oxidized
7	Surface black and gray, some small rust deposits	Surface black and gray
8	Similar to number 4 but rust chipped off in smaller pieces and surface beneath layer washed light rust color	Rough surface evenly oxidized
9	Rusty surface but no flaking more granular	Smoother surface than other samples but covered with rust, number clearly visible

TABLE E9

DESCRIPTION OF SAMPLES AT POINT 13

FIRST PERIOD

Coupon No.	Initial Appearance	Appearance After Washing
1	Covered with fly ash	No corrosion
2	Covered with fly ash	No corrosion
3	Covered with fly ash	No corrosion
4	Covered with fly ash	No corrosion
5	Covered with fly ash	Like no. 4 but light color and narrow ribbons of rust approximately 1 mm. wide and parallel. Also curved around mounting hole
6	Covered with fly ash	Same as no. 4 but corroded around mounting hole
7	Covered with fly ash	Fly ash scorched to surface
8	Covered with fly ash	Rusted, rough surface
9	Covered with fly ash	Rough surface

TABLE E10

DESCRIPTION OF SAMPLES AT POINT 3

SECOND PERIOD

1	Covered with fly ash	Stainless shine no visible corrosion
2	Covered with fly ash	Stainless shine no visible corrosion
3	Covered with fly ash	Stainless shine no visible corrosion
4	Covered with fly ash	Reddish-black oxide along cold roll grains
5	Covered with fly ash	Reddish-black oxide along cold roll grains
6	Covered with fly ash	Reddish-black oxide along cold roll grains
7	Covered with fly ash	Rust-red patches in gray metallic surface

during a series of reheat burner start-ups and test. During these tests (two weeks intermittently) the temperature varied between ambient and 400°F. The atmosphere was a dilute flue gas. Table E11 describes the coupons.

Conditions at Location "5"

Conditions at Location 5 were similar to 4 except during the reheat burner test when the temperatures were slightly elevated. Table E12 describes the sample coupons.

Conditions at Location "8" (2nd period)

Coupons at pt "8" during this period were at ambient conditions for most of the test period. The only abnormalities being the presence of catalyst dust. During a very short period of burner tests, temperatures were slightly above ambient at this location. Table E13 describes the coupon appearance.

Conditions at Location "10"

Conditions at pt 10 were also near ambient conditions for most of the test with the exception of about 5 days when the burner was being tested. Temperatures at 10 were slightly elevated during the tests. Also for about one month acid was stored in the absorbing tower hence the coupons were exposed to some acid gases during this period. However, overall conditions were less corrosive then the prior test period. Table E14 describes the appearance of the samples on removal and washing.

TABLE E11

DESCRIPTION OF SAMPLES AT POINT 4

SECOND PERIOD

1. No corrosion deposits clean surface	Minor pitting most prevalent at mounting hole
2. No corrosion deposits clean surface	Very minor pitting almost unnoticeable
3. No corrosion deposits clean surface	same as #1
4. No corrosion deposits rusted surface	Even and tightly bound rust surface
5. No corrosion deposits rusted surface	Tightly bound but slightly pitted rusted surface
6. No corrosion deposits rusted surface	same as #5
7. Dark gray over surface	same as before washing
8. Rusted flaky surface	Some tightly bound flakes and uneven surface
9. Rusted surface, granular, loose and uneven	Uneven rusted surface

TABLE E12

DESCRIPTION OF SAMPLES AT POINT 5

SECOND PERIOD

(no difference was noted before or after washing)

1. No deposits appearance before and after washing tarnished, no visible corrosion
2. No deposits appearance the same before and after washing tarnished very minor pitting
3. same as #1
4. Black burned appearance tiny localized rust along same grain boundaries
5. same as #4
6. same as #4

(Initially covered with catalyst dust)

TABLE E13

DESCRIPTION OF SAMPLES AT POINT 8

SECOND PERIOD

(No difference was noted after washing except that all coupons had an initial light coating of catalyst on removal from location.)

1. Clean surface tarnished (like high temperature discoloration)
2. Clean surface - very tiny pits (unnoticeable without magnifying glass)
3. Same as #1
4. Black color with localized reddish black rust - tightly bound
5. Same as #4
6. Same as #4
8. Evenly rusted surface fairly tight bound
9. Metallic gray with localized rust over most of surface
10. Darker tarnished color
11. Clean surface
12. Clean surface
13. Clean surface

TABLE E14

DESCRIPTION OF SAMPLES AT POINT 10

SECOND PERIOD

	Before Washing	After Washing
1.	Small deposits of salt spotting the surface	Surfaced covered with tiny pits similar to sand blasting effect (pits deepen under salt spots).
2.	Same as #1	Similar to #1, less pitting.
3.	Same as #1	Similar to #1, plus blue-green stain in one area on surface.
4.	Salt deposits spotting surface layer as #1	Rusted surface (small loose flakes) with tightly bound rust beneath flakes. Areas where deposit of were are not rusted but considerable metal is gone.
5.	Same as #4	Same as #4
6.	Same as #4	Same as #4
7.	Same as #4	Black-gray surface - no visible corrosion.
8.	Same as #4	Same as #4 but more granular rather than flaky.
9.	Same as #4	Same as #8

Conditions at Location "11"

Conditions at pt 11 were ambient with some traces of stack gas in the atmosphere in this area; however (since the by-pass plate was closed during this test period) the overall conditions were much less corrosive than the prior test period. Table E15 describes the appearance of the samples.

Conditions at Point "B"

Coupons at this location were exposed to acid for about 1 month of the test period. Acid strength was between 55 percent and 70 percent H_2SO_4. During the rest of this test period the location was either empty or filled with water. Temperature was ambient. Table #9 describes the sample appearance. See Table E16.

Conditions at Point "C"

Conditions at location "C" were the same as at "B" except that direct exposure to acid only took place when the product pump was running, hence exposure was minimized. See Table E17 for sample appearance.

Conditions at Point "D"

The coupons in "D" were exposed for a test period including test periods 1 and 2 for other coupons. They were not removed during the first test period due to difficult access.

Acid was stored in the base of the absorbing tower for about 6 months of this test period, hence it would be expected that the coupons were exposed to some acid gases during this period along

TABLE E15

DESCRIPTION OF SAMPLES AT POINT 11

SECOND PERIOD

	Before Washing	After Washing
1.	Covered with specks of rust	Extensive pitting.
2.	Same as #1	Extensive pitting, some exceed 1/64".
3.	Same as #1	Extensive pitting.
4.	Rusted (loose) flakey surface	Tightly bound rust, surface pitted.
5.	Same as #4	Same as #4.
6.	Same as #4	Flaky surface - tightly bound.
7.	Grey-black surface	Same as before washing.
8.	Rusted (loose) flaky and granular surface	Granular rust surface - tightly bound.
9.	Same as #8	Fine granular rust surface tightly bound.

TABLE E16

DESCRIPTION OF SAMPLES AT LOCATION B

SECOND PERIOD

1.	Clean surface	No visible corrosion.
2.	Clean surface	No visible corrosion.
3.	Clean surface	No visible corrosion.
7.	Clean surface	No visible corrosion.
12.	Covered with blue (salt) deposits (appears copper sulphate)	Stained surface-some metal corrosion visible.
14.	Clean surface	Clean surface--no corrosion.
15.	Covered with blue (salt) deposits	Stained surface-heavy grain boundary corrosion.
16.	Clean surface	Dark-gray - no visible corrosion.

TABLE E17

DESCRIPTION OF SAMPLES AT POINT "C"

SECOND PERIOD

1.	Clean surface -some salt deposits.	Clean, no visible corrosion.
2.	Clean surface - some salt deposits.	Clean, no visible corrosion.
3.	Clean surface - some salt deposits.	Clean, no visible corrosion.
4.	Rust, frosted with salt deposits.	Pitted and tight, rusted surface.
5.	Rust, frosted with salt deposits.	Pitted and tight, rusted surface.
6.	Rust, frosted with salt deposits.	Pitted and tight, rusted surface.
7.	Clean surface--some salt deposits.	Dark gray color - no visible corrosion.
10.	Clean surface--some salt deposits.	Tiny pitted surface.
11.	Clean surface--some salt deposits.	No visible corrosion.
12.	Clean surface--some salt deposits. Some copper rust with coating on coupon.	Stained surface--some small minor pitting.
12p.	Clean surface--some salt deposits. Some copper color coating on coupon.	Stained surface--some small minor pits.
13.	Clean surface--some salt deposits.	No visible corrosion.
14.	Clean surface--some salt deposits.	No visible corrosion.
15.	Frosted with blue salt deposits on surface.	Some pitting and corrosion along grain boundaries.

with some very dilute flue gas which backed up from the open by-pass at Pt. 11. The coupons were exposed to operating conditions for less than two weeks during the next test period. Other than this time temperatures were never ambient. See Table E18 for coupon appearance description.

TABLE E18

DESCRIPTION OF SAMPLES AT POINT "D"

SECOND PERIOD

*The mist eliminator was washed prior to removal of these samples, hence no before wash observations are possible.

1. Surface covered with localized pitting > 1/64" in size.
2. Surface covered with localized pitting - more intensive than #1. (size 1/64")
3. Surface pitted worse than #1 - less than #2.
4. Rusted surface tightly bound beneath granular loose cover.
5. Rusted surface tightly bound beneath granular loose cover.
6. Rusted surface - flakey (small flakes) rough surface.
7. Stained with rust from elsewhere light gray.
8. Same as #4.
9. Rusted surface - very fine granular surface, evenly covered.